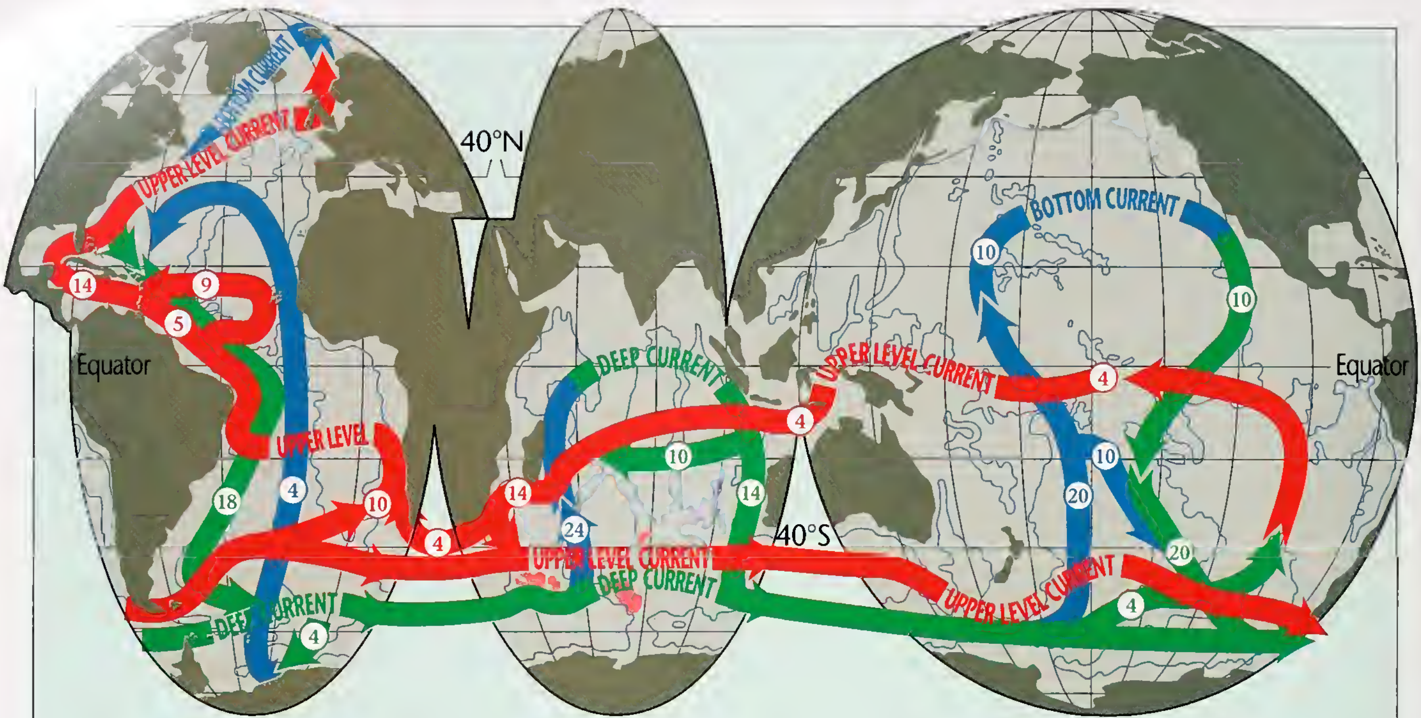
Oceanus

REPORTS ON RESEARCH FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

Vol. 39, No. 2 • Fall/Winter 1996 • ISSN 0029-8182

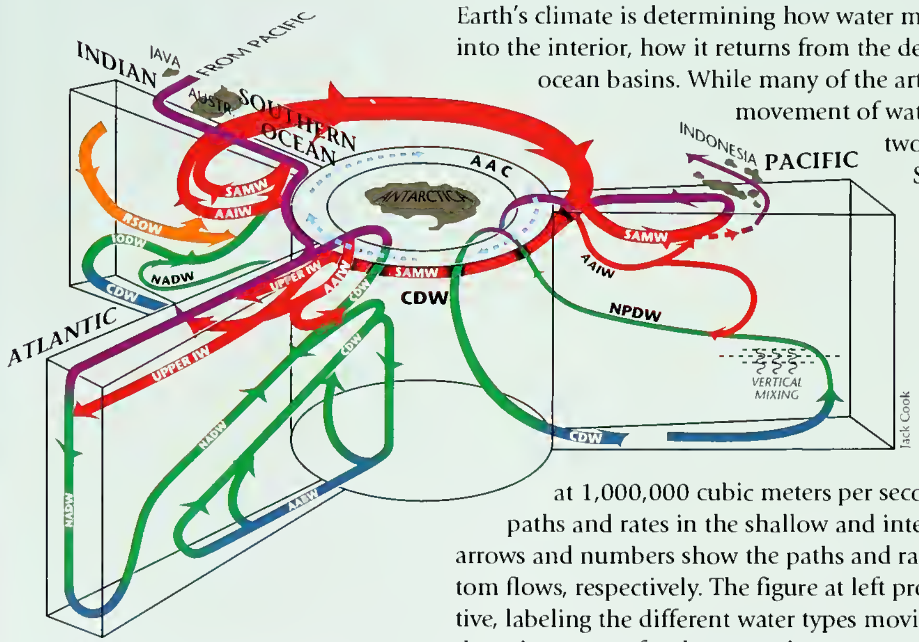
Oceans & Climate



The Ocean Conveyor Belt Flows Around the World

One of the keys to understanding how and on what time scales the vast volume of water in the ocean interacts with the atmosphere and modifies Earth's climate is determining how water moves from the surface of the ocean into the interior, how it returns from the depths, and how it flows between the ocean basins. While many of the articles in this issue focus on the movement of water within the North Atlantic, these two recent figures from WHOI Senior Scientist Bill Schmitz provide a global synthesis of the present understanding of the movement of water between ocean basins and across the depths.

The numbers in the top figure are flow rates or transports in units called Sverdrups (after Norwegian oceanographer Harald U. Sverdrup), which represent flow at 1,000,000 cubic meters per second. The red arrows show flow paths and rates in the shallow and intermediate depths. Green and blue arrows and numbers show the paths and rates for the deep ocean and for bottom flows, respectively. The figure at left provides a three-dimensional perspective, labeling the different water types moving along the pathways and adding the color orange for the very salty, warm water that flows out of the Red Sea, along with the color purple indicating near-surface circulations. These two figures are part of what Bill Schmitz, who holds the W. Van Alan Clark, Jr., Chair for Excellence in Oceanography, calls his "final report," a summary (in a somewhat speculative vein, he says) of what he has learned over the past 35 years about large-scale, low-frequency ocean currents. This two volume work is being published as part of the WHOI Technical Report series.



SAMW	Subantarctic Mode Water
AAIW	Antarctic Intermediate Water
RSOW	Red Sea Overflow Water
AABW	Antarctic Bottom Water
NPDW	North Pacific Deep Water
AAC	Antarctic Circumpolar Current
CDW	Circumpolar Deep Water
NADW	North Atlantic Deep Water
UPPER IW	Upper Intermediate Water
IODW	Indian Ocean Deep Water

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Cover: R/V *Oceanus* weathers a North Atlantic storm during a March 1981 study of a warm core ring spawned by the Gulf Stream. ***Inset:*** Researchers aboard R/V *Endeavor* (University of Rhode Island), an *Oceanus* sister ship, wrestle with a rosette water sampler in the southern Labrador Sea during a spring 1991 investigation of the origins of the deep western boundary current.
Large photo by James McCarthy, Harvard University. Inset by Peter Landry, WHOI

Oceanus is published semi-annually by the Woods Hole Oceanographic Institution, Woods Hole, MA 02543. 508-289-3516. http://www.whoi.edu/oceanus

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Checks should be drawn on a US bank in US dollars and made payable to Woods Hole Oceanographic Institution.

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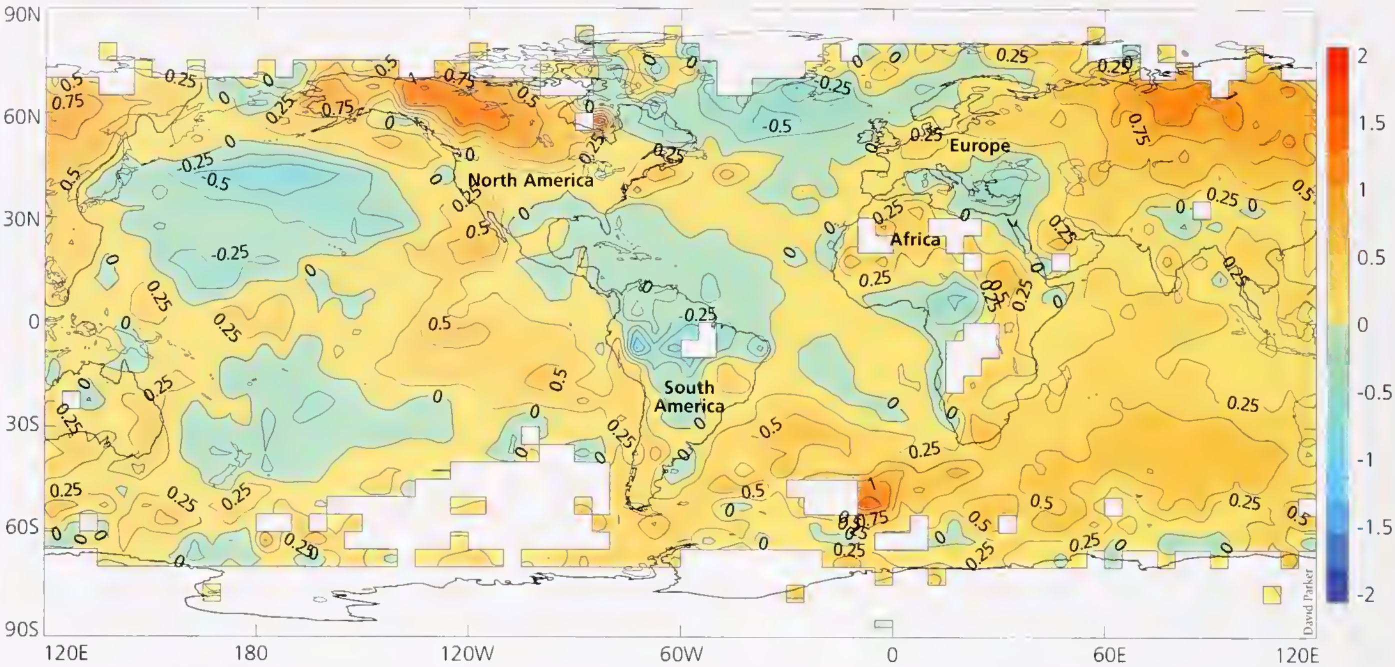
Oceans & Climate



Annual surface temperature change in degrees Centigrade for the period 1975–1994 relative to 1955–1974. This figure, prepared for the 1996 Intergovernmental Panel on Climate Change, indicates that Earth's surface has been, on average, warmer (predominating orange) over the past 20 years compared to the preceding 20 years. The cooler blue areas show, however, that the warming has not been universal.

Oceans & Climate

The Ocean's Role In Climate & Climate Change

Michael S. McCartney

Senior Scientist, Physical Oceanography Department

The past decade has brought rapid scientific progress in understanding the role of the ocean in climate and climate change. The ocean is involved in the climate system primarily because it stores heat, water, and carbon dioxide, moves them around on the earth, and exchanges these and other elements with the atmosphere. Three important premises of the oceans and climate story are:

- The ocean has a huge storage capacity for heat, water, and carbon dioxide compared to the atmosphere.
- Global scale oceanic circulation transports heat, water, and carbon dioxide horizontally over large distances at rates comparable to atmospheric rates.
- The ocean and atmosphere exchange as much heat, water, and carbon dioxide between them as each transports horizontally.

The ocean and atmosphere are coupled—their "mean states," evolution, and variability are linked. Ocean currents are primarily a response to exchanges of momentum, heat, and water vapor between ocean and atmosphere, and the resulting ocean circulation stores, redistributes, and releases these and other properties. The atmospheric part of this coupled system exhibits variability through shifts in intensity and location of pressure centers and pressure gradients, the storms that they spawn and steer, and the associated distributions of temperature and water content. Oceanic variability includes anomalies of sea surface temperature, salinity,* and sea ice, as well as of the internal distribution of heat and salt content, and changes in the patterns and intensities of oceanic circulation. These coupled ocean–atmosphere changes may impact the land through phases of drought and deluge, heat and cold, and storminess.

One example of coupled ocean-atmosphere variability is the El Niño/Southern Oscillation or ENSO (see article on page 39). The appearance of warm water at the ocean's surface in the eastern tropical Pacific off South America has a dra-

*Many of this issue's articles discuss the physical properties of seawater. The density of seawater changes with temperature (measured in °C), salinity (measured in parts per thousand or grams of salt per kilogram of water—typically given without units, such as simply 34.9), and pressure. The density of seawater (ρ) in kilograms per cubic meter is close to and slightly larger than 1,000 kilograms per cubic meter. "Potential density," (σ), is the value of the relative density if the seawater is brought to the surface without exchanging heat on its way up. This expression helps oceanographers understand the water column's stability.

Our thanks to Senior Scientist Robert A. Weller for editorial assistance with this issue.

matic impact on weather and seasonal-to-interannual climate. Considerable effort has been dedicated to developing the ability to predict ENSO, including deployment and maintenance of buoys and other observational systems in the tropical Pacific and sustained attention to improving models of ENSO. However, ENSO is but one of the mechanisms by which the ocean and atmosphere influence one another. Such coupling occurs on many time scales, even over centuries (see "Sedimentary Record" article on page 16). There is growing interest among the oceanographic community in developing a better understanding of the ocean's role in climate changes on decadal to centennial time scales, and many of the articles in this issue focus on such variability in the North Atlantic Ocean.

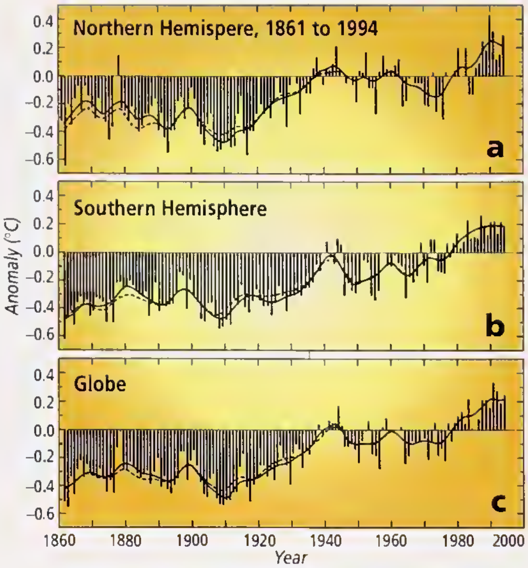
There are, as yet, no continuing observations dedicated, as the observing network in the tropical Pacific is to ENSO, to monitoring, understanding, and predicting decadal climate variability involving ocean-atmosphere interaction. Our challenges are to learn from what observations and modeling *have* been done and to develop strategies for future work.

Sustained observations allow scientists to detect climatic spatial patterns. For example, the figure opposite shows interdecadal change in land and sea surface temperatures. This figure is taken from the 1996 Intergovernmental Panel on Climate Change (IPCC) report, a huge effort of the international climate research community to assess Earth's climatic state every five years. The predominating orange indicates that the earth's surface has been, on average, warmer the past 20 years compared to the preceding 20 years. Significant blue areas, principally over the oceans, show that the warming has not occurred everywhere: Large areas of the subpolar North Atlantic are cold, sandwiched between warm northern North America and northern Eurasia, and the North Pacific is also cold, but with a subtropical emphasis rather than a subpolar emphasis.

The figure above right puts a longer time perspective on the warming by showing the hemispheric and global average temperature over the past 135 years, the rough limit of useful sustained measurements. These curves show the overall global warming beginning with the industrial age, but note the roughly 60 year oscillation this century, particularly in the northern hemisphere, showing steeper warming trends 1910–1940/1945 and 1975–1995. Time series like these lie at the heart of controversies about global warming as a trend versus as a phase of some mode of "natural" climate variability.

Continued sustained measurements of a broad array of climate indicators will eventually directly answer key questions: Is the steep temperature rise of the past 20 years the portent of a crisis: a rise that will continue through the next century and evolve into an increasingly major climate perturbation? Or is the steep rise "just" a phase of a natural oscillation of the climate system superimposed on a less severe warming? Or is the entire warming trend of the past 135 years itself just the warming phase of a still longer natural oscillation? There is a preponderance of scientific judgement, as carefully compiled and described by the IPCC, that the answer will be somewhere between the first two possibilities, and that this is caused by human impact on the climate system.

This issue of *Oceanus* emphasizes the North Atlantic Ocean, but, to answer these scientific questions, we must also take on the challenges of filling in many sparsely sampled regions, building on the ENSO work in the Pacific and decadal variability research in the North Atlantic, and working toward understanding on a global basis.



Jayne Doucette

Hemispheric and global average temperature for the past 135 years.

Craig Dickson

Scientists aboard R/V *Knorr* launch a rosette water sampler and conductivity/temperature/depth instrument. Much of the data discussed in this issue was collected by such equipment. Author McCartney is the fellow getting wet at top left.

If Rain Falls On the Ocean—

Does It Make a Sound?

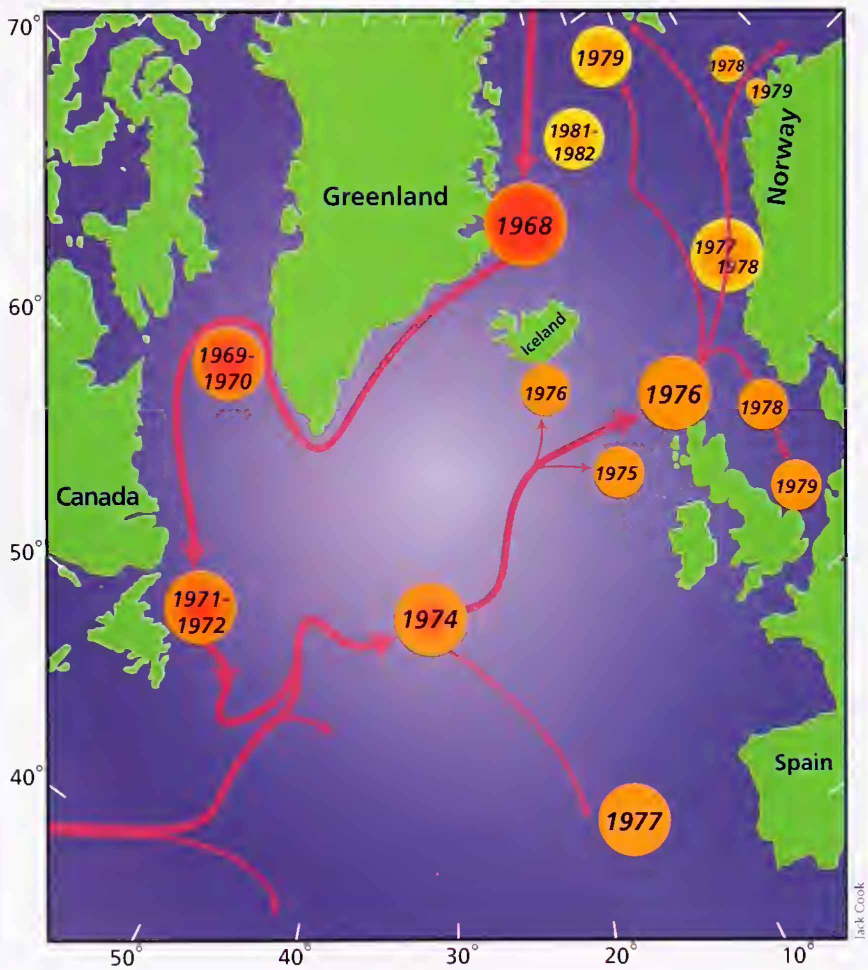
Fresh Water's Effect on Ocean Phenomena

Raymond W. Schmitt
Senior Scientist, Physical Oceanography

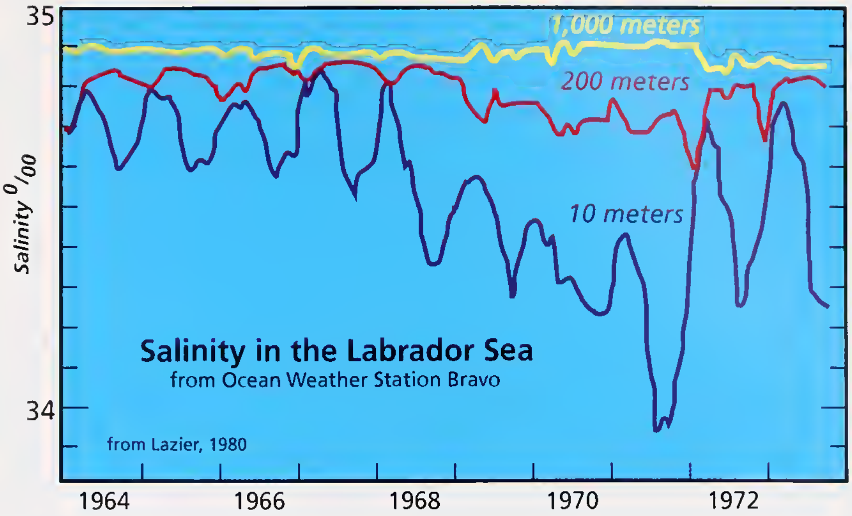
As with similar questions about a tree in the forest or a grain of sand on the beach, it may be hard to imagine that a few inches of rain matters to the deep ocean. After all, the ocean's average depth is around 4 kilometers and only 1 to 5 centimeters of water are held in the atmosphere at any one time. But it *does* matter, in part because the ocean is salty. The effect of rain diluting the salts in the ocean (or evaporation concentrating them) can be greater than the effect of heating (or cooling) on the density of seawater.

It also matters because rainfall and evaporation are not evenly distributed across and among ocean basins—some regions continuously gain water while others continuously lose it. This leads to ocean current systems that can be surprisingly strong. The processes of evaporation and precipitation over the ocean are a major part of what is called "the global water cycle;" indeed, by all estimates, they dominate the water cycle over land by factors of ten to a hundred. The addition of just one percent of Atlantic rainfall to the Mississippi River basin would more than double its discharge to the Gulf of Mexico.

As discussed previously in *Oceanus*, our knowledge of the water cycle over the ocean is extremely poor (see the Spring 1992 issue). Yet we now realize that it is one of the most important components of the climate system. One of the significant pieces of evidence for this comes from a description of the "Great Salinity Anomaly" put together by Robert Dickson (Fisheries Laboratory, Suffolk, England) with other European oceanographers. The Great Salinity Anomaly (GSA) can be characterized as a large, near-surface pool of fresher water that appeared off the east coast of Greenland in the late 1960s (see figure at left). It was carried around Greenland and into the Labrador Sea



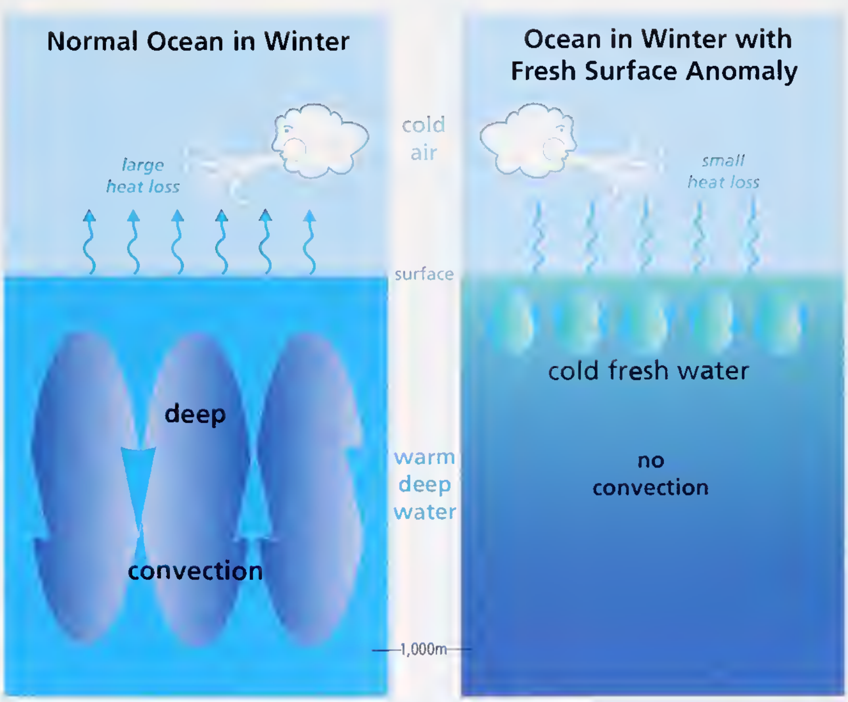
The Great Salinity Anomaly, a large, near-surface pool of fresher-than-usual water, was tracked as it traveled in the subpolar gyre currents from 1968 to 1982.



Salinity as a function of time at 10 meters, 200 meters, and 1,000 meters depth as recorded at Ocean Weather Station Bravo (see map on page 10) in the Labrador Sea. Deep convection is possible when the salinity difference between shallow and deep water is small. This normally occurs every winter. However, from 1968 to 1971, the presence of the fresh, shallow, Great Salinity Anomaly prevented deep convection. Unfortunately, Weather Station Bravo is no longer maintained. Scientists will need to use new technology like the PALACE float (see Box overleaf) in order to reestablish such time series. Such data is essential for understanding the role of freshwater anomalies in the climate system.

by the prevailing ocean currents, in the counterclockwise circulation known as the subpolar gyre. It hovered off Newfoundland in 1971–72 and was slowly carried back toward Europe in the North Atlantic Current, which is an extension of the Gulf Stream. It then completed its cycle and was back off the east coast of Greenland by the early 1980s, though reduced in size and intensity by mixing with surrounding waters. The origin of the Great Salinity Anomaly is thought to lie in an unusually large discharge of ice from the Arctic Ocean in 1967. Its climatic importance arises from the impact it had on ocean–atmosphere interaction in the areas it traversed.

The GSA derives its climate punch from the strong effect of salinity on seawater density, with salty water being considerably denser than fresh water. That is, these northern waters normally experience strong cooling in the winter, which causes the surface water to sink and mix with deeper waters. This process, called deep convection (see figure below), is a way for the ocean to release heat to the atmosphere, heat that then helps to maintain a moderate winter climate for northern Europe. However, when the GSA passed through a region, the surface waters became so fresh and light that even strong cooling would not allow it to convect into the deeper waters. Thus, the deep water remained isolated from the atmosphere, which could not extract as much heat as usual from the ocean. The GSA acted as a sort of moving blanket, insulating different parts of the deep ocean from contact with the atmosphere as it moved around the gyre. Its impact in the Labrador Sea has been particularly well documented (see "Labrador Sea" article on page 24). When the surface waters were isolated from deep waters, they became cooler. Changing sea surface temperature patterns can affect atmospheric circulation, and may possibly reinforce a poorly understood, decades-long variation in North Atlantic meteorological conditions known as the North Atlantic Oscillation (see box on page 13). For it is the ocean that contains the long-term memory of the climate system. By comparison, the atmosphere has hardly any thermal inertia. It is difficult to imagine how the atmosphere alone could develop a regular decadal oscillation, but the advection of freshwater anomalies by the ocean circulation



Deep convection is a key component of the ocean's role in Earth's climate. Strong winter cooling of surface waters causes them to become denser than water below them, which allows them to sink and mix with deeper water. This process releases heat from the overturned water to the atmosphere and maintains northern Europe's moderate winter climate. The Great Salinity Anomaly interrupted this process as its pool of fresher water prevented convection.

could be an important key to this climate puzzle.

Unfortunately, we have no ready means of detecting freshwater pulses like the GSA. While surface temperature can be observed easily from space, surface salinity, so far, cannot. The salinity variations important for oceanography require high precision and accuracy, so there is no quick and inexpensive method of measurement. We have had to rely on careful analysis of sparse historical records from mostly random and unrelated surveys gleaned from several nations to piece the GSA's story together. But how many other "near-great" salinity anomalies have we missed because the signal was not quite large enough? Is there a systematic way to monitor salinity so that we know years in advance of another GSA's approach?

In addition to variability *within* an ocean ba-

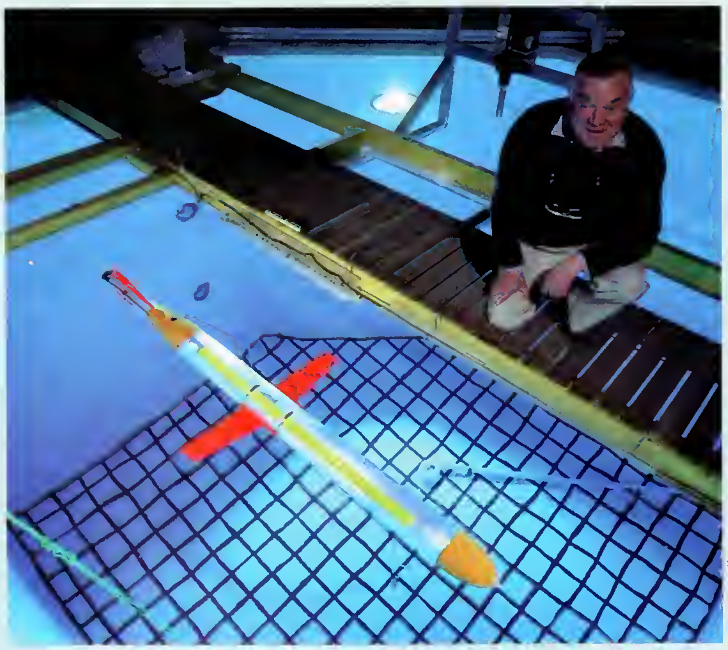
ALACE, PALACE, Slocum

A Dynasty of Free Floating Oceanographic Instruments

Autonomous diving floats have been developed by Doug Webb of Webb Research, Inc. in Falmouth, MA, in conjunction with Russ Davis of the Scripps Institution of Oceanography. The Profiling Autonomous LAgrangian Circulation Explorer (PALACE) is a free float that drifts with the currents at a selected depth, much like a weather balloon drifts with the winds. At preset time intervals (typically one or two weeks) it pumps up a small bladder with oil from an internal reservoir, which increases its volume, but not its mass, and causes it to rise to the surface. On the way up it records temperature and salinity as a function of depth. Once at the surface it transmits the data to a satellite system that also determines its geographical position. The drift at depth between fixes provides an estimate of the "Lagrangian" velocity at that time and place (as opposed to "Eulerian" measurements of the velocity past a fixed point. These names derive from 18th century mathematicians who originated these ways of looking at fluid flows).

The basic technology of the float has been used for several years in the nonprofiling ALACE, which simply provides velocity information. Hundreds of ALACES have been successfully deployed in the Pacific and Indian Oceans. A program to release a large number of PALACES in the Atlantic is just getting underway.

The use of the ALACE as a platform for salinity measurements is not without problems. The slow rising motion, and low power available, limit the type of sensor that can be deployed. The problem of sensor drift due to biological fouling may be severe in some regions, and methods to prevent fouling are just being developed. However, because the float spends most of its life in a deep and climatically stable water mass, not subject to near-surface atmospheric variations, we should be able to compensate for any drifts.


Tinco Ferorelli

Doug Webb was photographed on a catwalk above a test tank used to put the Slocum glider through its paces.

But the fact that these floats move around is something of a drawback if the objective is to monitor ocean temperature and salinity. That is, in the long run, we would rather that they stayed put and measured the properties in one place. Such a task could be achieved if the float were capable of gliding horizontally and turning as it rose. The horizontal displacement achieved could be directed to maintain one position, with each excursion compensating for the drift caused by ocean currents. With Navy funding, Webb, Davis, and Breck Owens (WHOI) are currently working on such a gliding float (see photo).

All these floats depend on batteries to power the electronic sensors, the pump that varies ballast, and the transmitter that sends data to the satellite. The battery life is around two years, depending on the frequency of profiling and transmitting. One way to extend its life is to use the ocean's vertical temperature differences to run a simple heat engine. Doug Webb has another type of float sin, we would like to understand the large differences in salt concentration *among* ocean basins. (see figure on next page) For example, the Pacific Ocean is significantly fresher than the Atlantic and, because it is lighter, stands about half a meter higher. This height difference drives the flow of Pacific water into the Arctic through the Bering Strait. The salinity difference between these two major oceans is thought to be caused by the transport of water vapor across Central America: The trade winds evaporate water from the surface of the Atlantic, carry it across Central America, and supply rainfall to the tropical Pacific. This water loss is the major cause of the Atlantic's greater saltiness and its propensity to form deep water. The extra rainfall on the Pacific makes it fresher and prevents deep convection. How does this atmospheric transport vary with

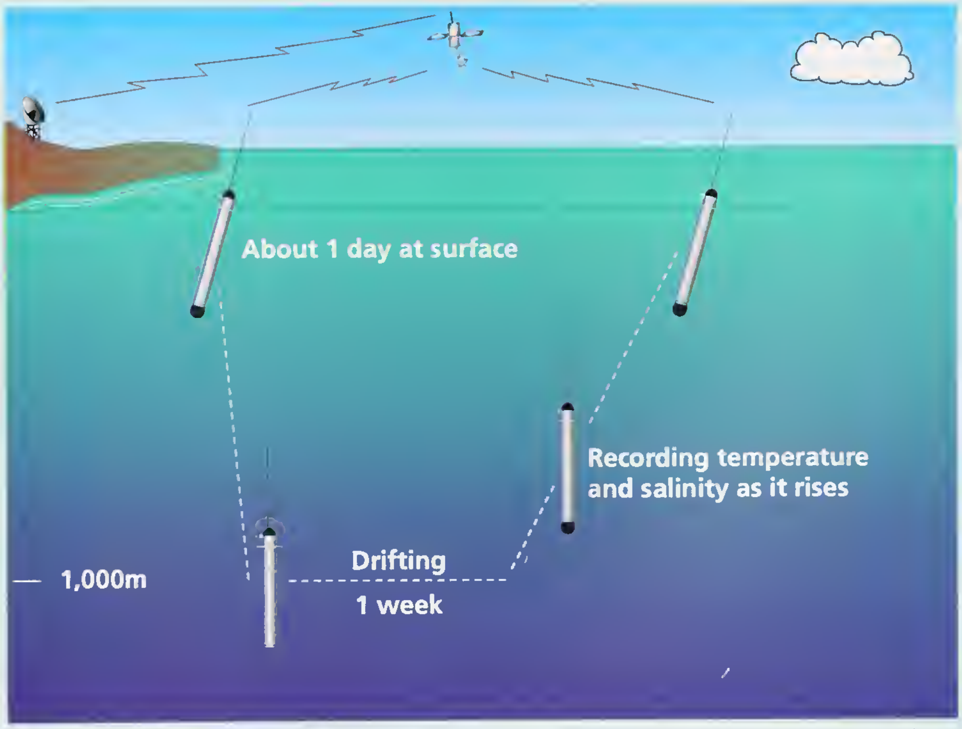
with such a propulsion system. It uses a waxy material that expands when it melts at around 50 degrees, a temperature the float encounters at several hundred meters depth on each trip to and from the surface. This expansion is used to store energy to pump ballast when needed. Use of this "free" energy for propulsion reduces the load on the batteries and extends the life of the float. The thermal ballasting engine has been tested extensively in the lab and recently deployed off Bermuda in a nongliding float, where it performed over 120 depth cycles.

Doug Webb's dream is to marry the thermal engine with the glider, and thus make a long-lived, roving (or station-keeping) autonomous profiler possible. Years ago he described the technical possibilities to the late Henry Stommel, who developed a vision of how such an instrument might be deployed in large numbers around the globe (see *Oceanus*, Winter 1989/90). They called the instrument Slocum, with the idea that it could circumnavigate the globe under its own power, like New Englander Joshua Slocum, the first solo sailor to perform that feat. The Internet could allow scientists to monitor Slocum data from their home laboratories around the world.

If we deploy enough Slocums, their data should be as valuable for predicting global climate on seasonal to decadal time scales as satellites and weather balloons are for forecasting the daily weather. Indeed, one of Slocum's key attractions is that it is inexpensive enough to deploy in large numbers. Per-profile costs for both temperature and salinity are expected to be $50 or less, once a mature system is operating—vastly cheaper than anything possible using ships. A globe-spanning array of 1,000 Slocums would cost less than a new ship, yet provide an unprecedented view into the internal workings of the global ocean. —*Ray Schmitt*


Sarah Zimmerman

MIT/WHOI Joint Program student Steve Jayne holds an ALACE (Autonomous LAgrangian Circulation Explorer) float aboard R/V *Knorr* during a 1995–1996 (yes, Christmas at sea) cruise for the World Ocean Circulation Experiment in the Indian Ocean.



Jack Cook

During a data collection and reporting cycle, a PALACE (Profiling Autonomous LAgrangian Circulation Explorer) float drifts with the current at a programmed depth, rises every week or two by inflating the external bladder (recording temperature and salinity profiles on the way up), spends a day at the surface transmitting data, then returns to drift at depth by deflating the bladder.

time? Since salinity is a good indicator of the history of evaporation or precipitation, perhaps if we had sufficient data, we could see changes in the upper ocean salt content of the two oceans that reflect variations in atmospheric transports. How many years does it take for salinity anomalies in the tropical Atlantic to propagate to high-latitude convection regions and affect the sea-surface temperature there? What is the impact on the atmospheric circulation?

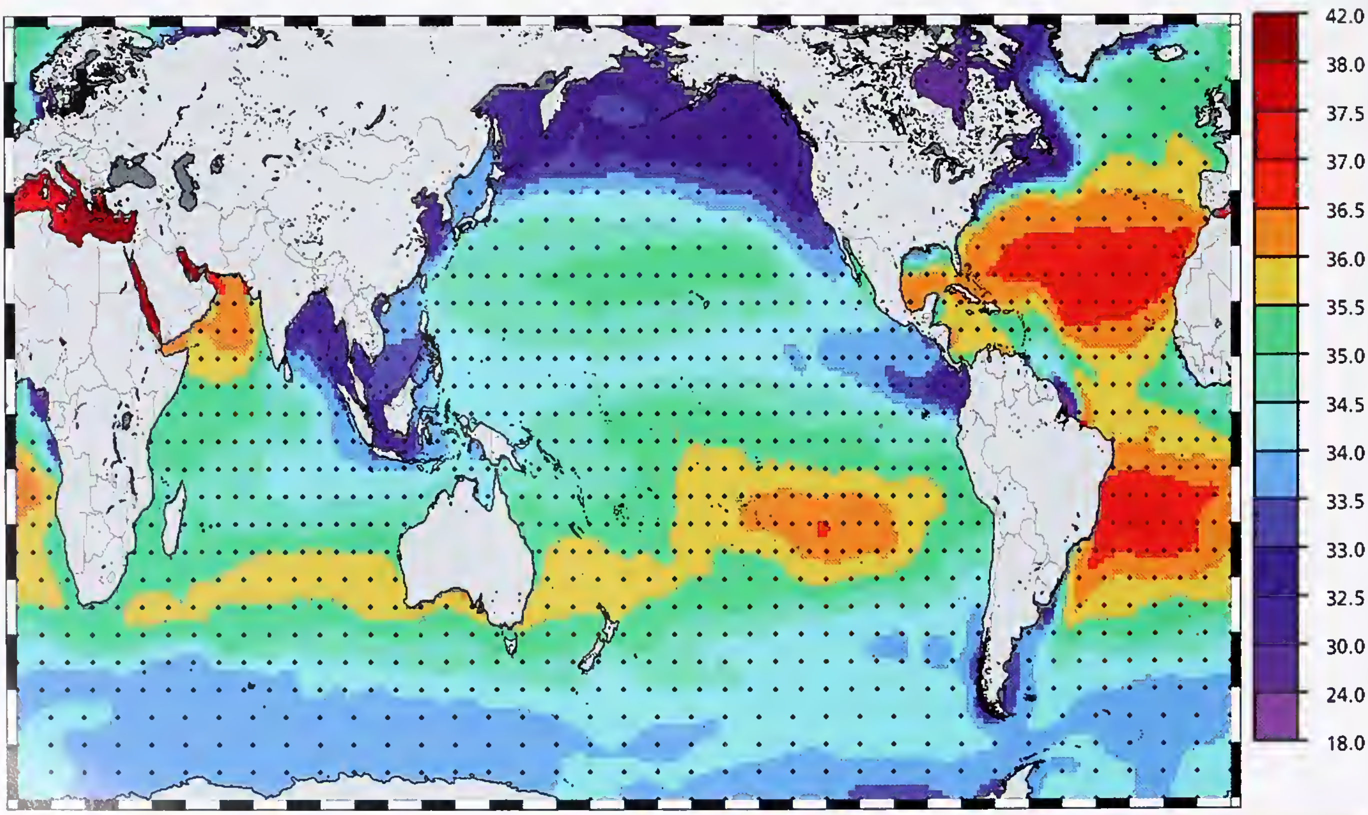
These and other climate problems will continue to perplex us until we make a serious attempt to monitor salinity on large space and time scales. One approach would be to maintain ships in certain places to sample the ocean continually. A modest effort along these lines was made after World War II when weather ships were maintained at specific sites by several nations (see following article). The data they collected provide nearly the only long time-series measurements available from deep-ocean regions. However, the weather ships are all but gone; there is only one now, maintained seasonally by the Norwegians. Today's satellites provide information on approaching storm systems, but, unfortunately, they cannot tell us what we need to know about ocean salinity distributions.

It now appears that new technology will provide the key to the salinity monitoring problem, at a surprisingly modest cost. The Box on pages 6 and 7 describes how we might obtain temperature and salinity profiles from data collected by autonomous diving floats. It should be quite feasible to deploy an array of these station-keeping "Slocums" that would intercept and monitor the progress of the "Great Salinity Anomalies" of the future. In the next two years, a large number of profiling ALACE (precursor to the Slocum) floats will be deployed in the Atlantic in a preliminary test of the general concept. In addition to measuring temperature and salinity, Slocums might some day measure rain. It turns out that rain falling on the ocean does make a sound, and work is underway to record that sound with hydrophones and develop algorithms to convert the measured sound level to rain rates.The remaining technical obstacles to development of a globe-spanning array of station-keeping Slocums are small. The only thing lacking is a strong societal commitment to the support of such fundamental research on the climate system of the earth.

This research was sponsored by the National Science Foundation and the National Oceanic and Atmospheric Administration's Climate and Global Change Program.

Most of Ray Schmitt's career has been focused on very small-scale processes in the ocean related to mixing by turbulence and "salt fingers." However, he has been driven toward studies of the global-scale hydrologic cycle by a desire to contribute to improved weather and climate prediction, so that he can better plan to take advantage of the rare good weather in Woods Hole.

The average surface salinity distribution in the global ocean, as compiled from many individual ship measurements, mostly during this century. The figure also shows the approximate coverage obtainable with an array of about 1,000 Slocums or PALACES. These would resolve the large scale features of the salinity field and provide completely new information on its variability with time. The array would be an early warning system for the Great Salinity Anomalies of the future.



US Coast Guard

Coast Guard Cutter *Sebago* was photographed on Station A in January 1949.

Alpha, Bravo, Charlie...

Ocean Weather Ships 1940–1980

Robertson P. Dinsmore
WHOI Marine Operations

The ocean weather station idea originated in the early days of radio communications and trans-oceanic aviation. As early as 1921, the Director of the French Meteorological Service proposed establishing a stationary weather observing ship in the North Atlantic to benefit merchant shipping and the anticipated inauguration of trans-Atlantic air service. Up to then, temporary stations had been set up for special purposes such as the US Navy NC-4 trans-Atlantic flight in 1919 and the ill-fated Amelia Earhart Pacific flight in 1937.

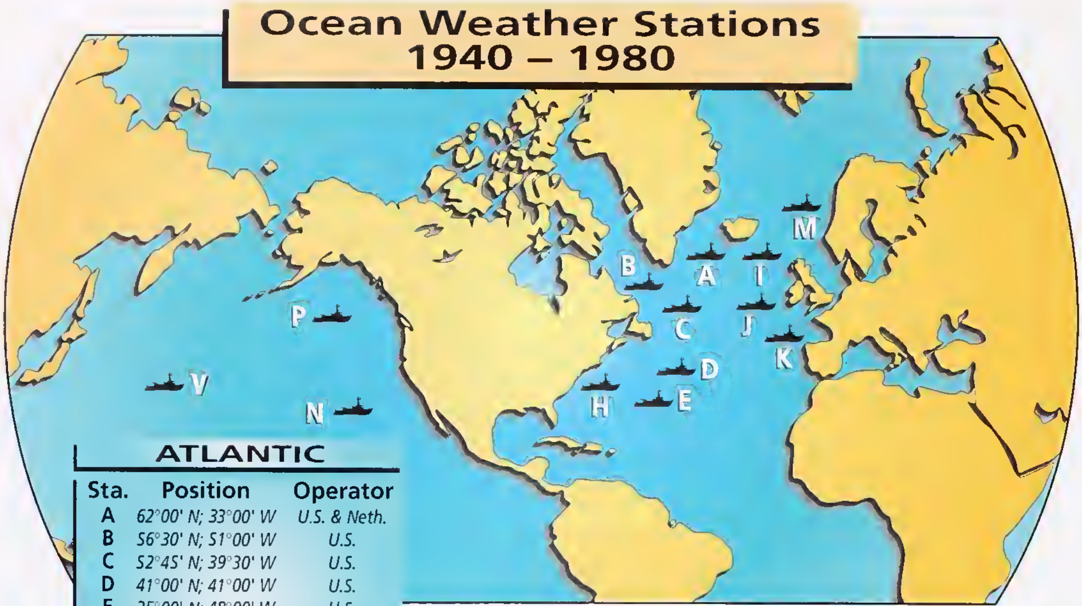
The loss of a PanAmerican aircraft in 1938 due to weather on a trans-Pacific flight prompted the Coast Guard and the Weather Bureau to begin tests of upper air observations using instrumented balloons. Their success resulted in a recommendation by Commander E. H. Smith of the International Ice Patrol (and future Director of the Woods Hole Oceanographic Institution) for a network of ships in the Atlantic Ocean.

World War II brought about a dramatic increase in trans-Atlantic air navigation, and in January 1940 President Roosevelt established the "Atlantic Weather Observation Service" using Coast Guard cutters and US Weather Bureau observers. Most flights at this time were using southern routes. On February 10, 1940, the 327-foot cutters *Bibb* and *Duane* occupied Ocean Stations 1 and 2—the forerunners of Stations D and E (see chart on next page).

With the US entering the war, Coast Guard cutters were diverted to anti-submarine duties, and the weather stations were taken over by a motley assortment of vessels ranging from converted yachts to derelict freighters, mostly Coast Guard operated. As trans-Atlantic air traffic increased, so did the number of weather and plane guard stations. The role of weather during the Battle of Coral Sea and trans-Pacific flights resulted in stations being set up in that ocean also. At the service's peak, there were 22 Atlantic and 24 Pacific stations.

At war's end, the Navy intended to discontinue weather ship operations, but pressure from several sources resulted instead in establishment of a permanent peacetime system of 13 stations. These are shown on the next page, with the positions and operating nations listed in the accompanying table. Costs of the program were shared by nations operating transoceanic aircraft.

A typical weather patrol was 21 days on-station. A "station" was a 210-mile grid of 10-mile squares, each with alphabetic designations. The center square, which the ship usually occupied, was "OS" (for "on-station"). A radio beacon



ATLANTIC

Sta.	Position	Operator
A	62°00' N; 33°00' W	U.S. & Neth.
B	56°30' N; 51°00' W	U.S.
C	52°45' N; 39°30' W	U.S.
D	41°00' N; 41°00' W	U.S.
E	35°00' N; 48°00' W	U.S.
H	36°00' N; 70°00' W	U.S.
I	61°00' N; 15°00' W	U.K.
J	52°30' N; 20°00' W	U.K.
K	45°00' N; 16°00' W	France
M	66°00' N; 02°00' E	Norway

PACIFIC

Sta.	Position	Operator
N	30° N; 140° W	U.S.
P	50° N; 145° W	Canada
V	34° N; 164° E	U.S.

Jayne Doucette

Map shows the 13 permanent weather stations established in 1946 by the United Nations Civil Aviation Organization Program costs were shared by nations operating transoceanic aircraft. Letters missing from the alphabetical sequence were those used for stations occupied during World War II but not included in the postwar weather station program.

transmitted the ship's location. Overflying aircraft would check in with the ship and receive position, course and speed by radar tracking, and weather data. Surface weather observations were transmitted every three hours, and "upper airs"—from instrumented balloon data—every six hours. Using radiosonde transmitters and radar tracking, balloon observers obtained air temperature, humidity, pressure, and wind direction and speed to elevations of 50,000 feet.

Oceanographic observations were recommended for weather ships almost from the start. Beginning in 1945 and continuing to the end, US ships made bathythermograph (B/T) observations that today constitute the largest B/T archive in existence. Many specific, short-term programs were carried out with oceanographers frequently riding the ships. In addition to serving as weather reporters and navigation aids, weather ships occasionally rescued downed aircraft and foundering ships. Dramatic weather station rescues include the Bermuda Sky Queen in 1947 (Station C), Pan-American 943 (Station N) in 1956, and SS Ambassador (Station E) in 1964.

By 1970, new jet aircraft were coming to rely less on fixed ocean stations, and satellites were beginning to provide weather data. In 1974, the Coast Guard announced plans to terminate the US stations, and, in 1977, the last weather ship was replaced by a newly developed buoy. The international program ended when the last ship departed Station M in 1981.

Capt. Dinsmore commanded the weather ship USCGC Cook Inlet. *During his 28-year Coast Guard career, he served on four North Atlantic weather ships and was weather ship program manager before joining the WHOI Staff in 1971. This article is exerpted from a text about twice this length. Interested readers may request the longer account from the Oceanus office by calling 508-289-3516 (email: oceanusmag@whoi.edu).*

US Coast Guard

Weather balloons were released from weather ships every six hours to gather data from elevations as high as 50,000 feet.

A Century of North Atlantic Data Indicates Interdecadal Change

Surface Temperature, Winds, & Ice in the North Atlantic

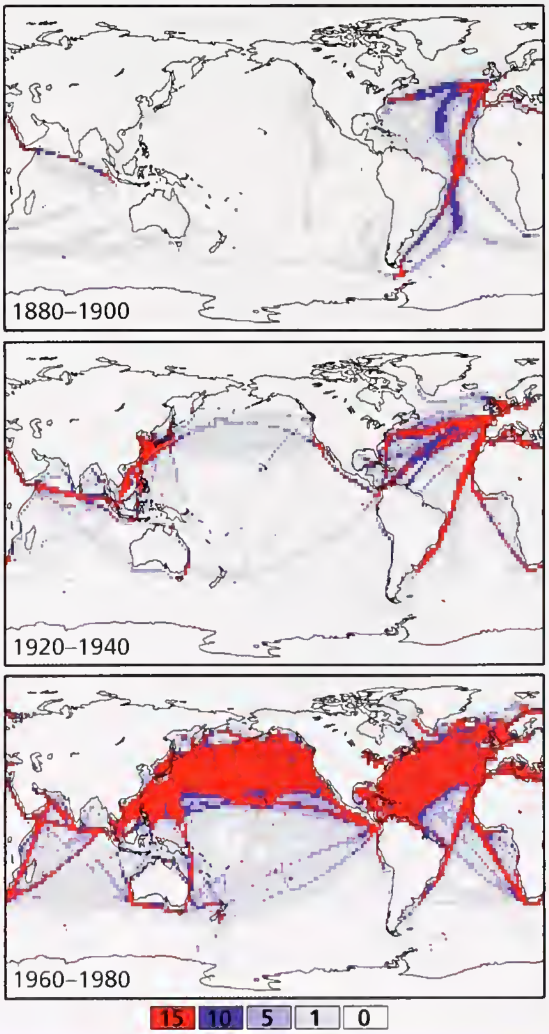
Clara Deser
Research Associate, University of Colorado

For hundreds of years mariners have recorded the weather over the world ocean. Some 100 million marine weather reports have accumulated worldwide since 1854, when an international system for the collection of meteorological data over the oceans was established. These reports include measurements of sea surface temperature, air temperature, wind, cloudiness, and barometric pressure. In the 1980s, the National Oceanic and Atmospheric Administration (NOAA) compiled these weather observations into a single, easily accessible digital archive called the Comprehensive Ocean-Atmosphere Data Set. This important data set forms the basis for our empirical knowledge of the surface climate and its variability over the world's oceans: One example of a variable system is the phenomenon known as El Niño in the tropical Pacific (see article on page 39). A major challenge in climate research is to use these data to document and understand the role of the oceans in long-term—decadal and centennial—climate change.

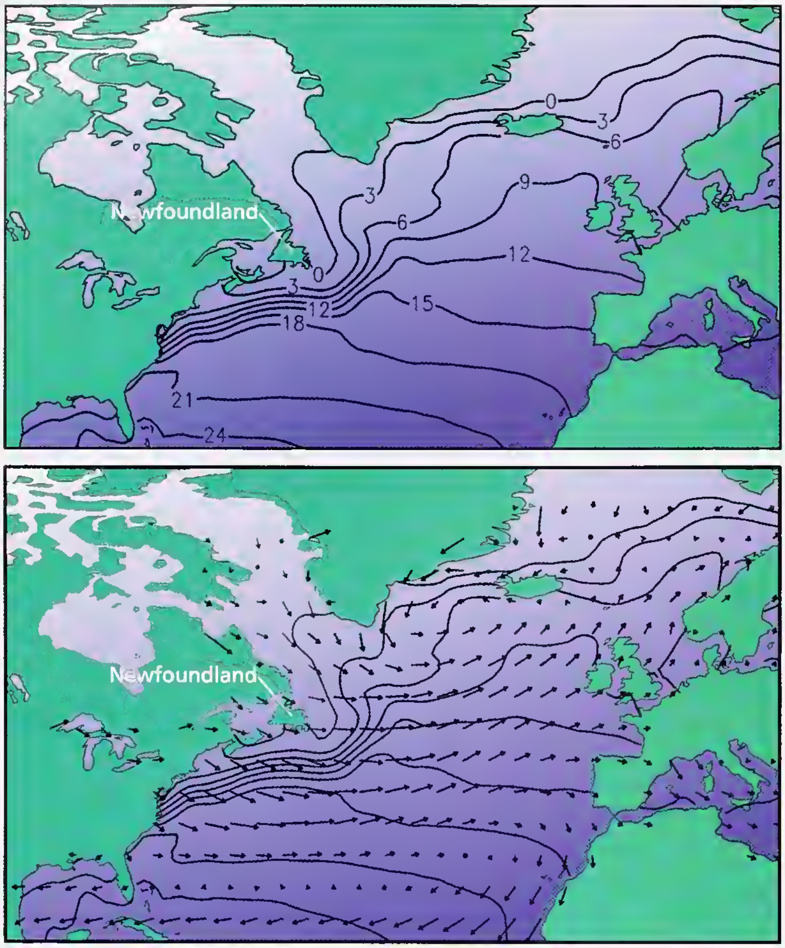
The figure at right shows the geographical distribution of weather observations over the oceans for three periods: 1880–1900, 1920–1940, and 1960–1980. Before the turn of the century, marine weather reports were largely restricted to shipping lanes in the North Atlantic and western South Atlantic. The North Pacific was not well sampled until after World War II, and the tropical oceans not until after about 1960; the southern oceans are still largely unmeasured. Due to the irregular sampling, we focus on describing climate variations over the North Atlantic back to the turn of the century. Fortunately, the North Atlantic plays an important role in world-ocean circulation.

Two parameters are of key importance to the physical interaction between ocean and atmosphere: sea-surface temperature and near-surface wind. They control the rates of heat and momentum transfer between the two media. The top figure on page 12 displays the long-term average distributions of sea-surface temperature and near-surface wind over the North Atlantic. These charts are based upon all available observations since 1900. The prevailing westerly winds or "westerlies" are a well-known feature of the wind distribution. Sea surface temperatures are generally warmer in the East Atlantic than in the West Atlantic at the same latitude, reflecting the moderating influence of the Gulf Stream.

How have the wind and temperature distributions changed with time? A statistical technique called empirical orthogonal function analysis aids in identifying regions of coherent temporal

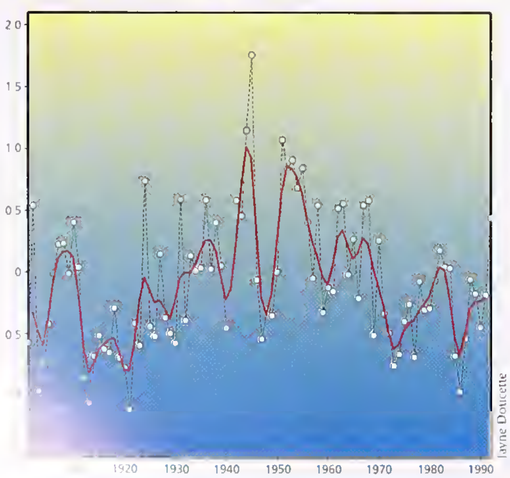


Geographical distribution of weather reports over the world. Colored areas show the average number of weather reports per month in each 2° latitude by 2° longitude square over the world oceans for each of the time periods indicated. White areas indicate there are no reports.



Average distributions of sea surface temperature (°C) (top) and near surface wind climatology (bottom) over the North Atlantic since 1900. The longest wind arrow corresponds to 8 meters per second.

change. The results of the statistical analysis point to the area directly south and east of Newfoundland as a site of pronounced sea surface temperature variability. The figure below shows the history of sea surface temperatures in this region since 1900. There is a notable tendency for cold and warm periods to be spaced approximately one decade apart, as well as longer-term warming and cooling trends that span several decades.



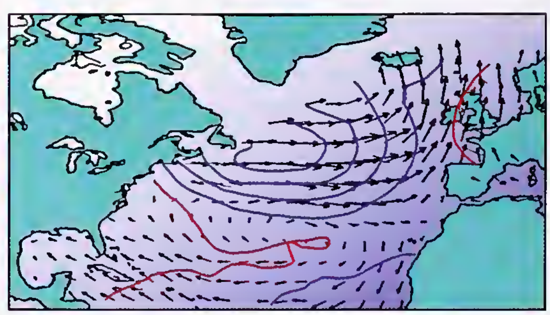
[illegible] sea surface temperatures for the region [illegible] and east of Newfoundland since 1[illegible] departures from normal in degre[illegible] red curve is a low-pass filtered version [illegible] curve, emphasizing fluctuations long[illegible] few years.

When the near-surface wind field is analyzed in a similar manner (but independently from the sea surface temperatures), similar decadal-scale oscillations and longer term trends are evident. As noted in the box on the opposite page, this basin scale pattern of variability has been labeled the North Atlantic Oscillation.

What is the nature of these decadal and multi-decadal fluctuations? Are they surface signatures of oscillations inherent to the deep ocean circulation? Are they global or confined to the North Atlantic? What is the role of the atmosphere? There is mounting evidence from mathematical models that the North Atlantic Ocean's thermohaline (heat and density driven) circulation may behave as a damped oscillatory system at decadal-to-multidecadal frequencies, with the atmosphere supplying the energy to maintain the oscillations against dissipation. In order to test the relevance of hypotheses generated from the modeling work, further description of the observed climate record is needed.

A composite picture of the decadal-scale variations can be formed by averaging all of the cold (or warm) periods from the figure below left and subtracting the long-term mean. The figure directly below shows such an "anomaly" composite of the cold events. When sea surface temperatures to the east of Newfoundland are colder than normal, the near-surface westerly winds are stronger than normal. This relationship may be indicative of positive feedback between atmosphere and ocean: Stronger winds cool the ocean surface by enhancing evaporation and heat loss, while colder surface temperatures shift the latitude of the storm track and prevailing westerlies southward. Thus, the decadal swings in wind and temperature may be a manifestation of a coupled air-sea interaction process, in line with recent modeling results. What determines the time scale of the fluctuations, as well as their amplitude, are unsolved issues at this time.

The decadal fluctuations in sea surface temperature show an intriguing relation to the amount of sea ice in the Labrador Sea, as the top figure opposite shows. While information on sea ice dates back only to 1953, it is evident that each of the decadal swings of colder-than-normal temperatures was preceded by a period of greater-than-normal amounts of sea ice. The mechanism for this association is not well understood, although it is plausible that the cold, stable water mass resulting from melting ice could be carried by ocean currents into the re-

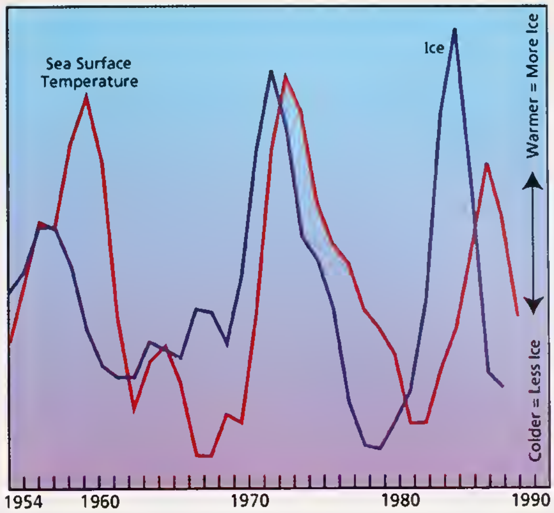


Composite of decadal-scale cold events in the North Atlantic using sea surface temperature and wind anomaly patterns since 1900. Blue (red) contours indicate colder (warmer) than normal sea surface temperatures. The longest wind arrow is 1 meter per second.

gion east of Newfoundland. Some researchers have hypothesized a complex feedback loop involving Arctic precipitation, runoff, salinity, and ocean circulation to explain the decadal-scale sea ice variations.

The lack of understanding of observed, long-term climate events in the North Atlantic underscores the need for further research, particularly in relating the deep ocean circulation to the surface conditions. The work described by Michael McCartney, Ruth Curry, and Hugo Bezdek beginning on page 19 is one important step in this direction.

This research was funded by a grant from the Atlantic Climate Change Program of the National Oceanic and Atmospheric Administration.



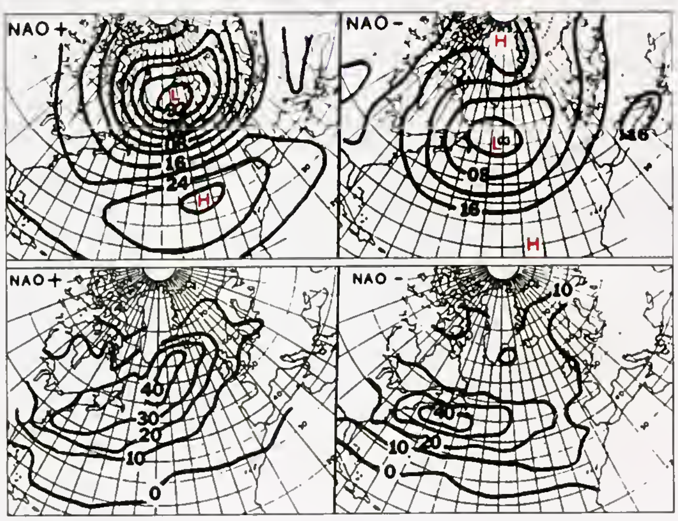
Jayne Doucette

History of sea ice amounts in the Labrador Sea in relation to sea surface temperatures in the North Atlantic since 1953.

Clara Deser was introduced to oceanography in 1983 while a Research Assistant in WHOI's Physical Oceanography Department. She then went to the University of Washington to obtain a Ph.D. in atmospheric sciences, and has since kept her feet wet and her head dry at the University of Colorado at Boulder. Currently, she continues her intellectual pursuits on a part-time basis while raising two children with her husband Jonathan.

North Atlantic Oscillation

The top two panels of the figure, sea level pressure in millibars, show an example of regional shifting climatic patterns. From work by Jeff Rogers of Ohio State University, they show the high (+) and low (-) extreme states of the North Atlantic Oscillation (NAO). The regional atmospheric circulation over the North Atlantic is normally characterized by a subpolar high pressure cell centered near the Azores, and a subpolar low pressure cell centered near Iceland and Greenland. Between these two centers the westerlies blow from North America towards Europe, while to the north of the Icelandic low, and to the south of the Azorian high the winds are easterlies. A characteristic oscillation of the strengths and positions of these pressure centers occurs interannually and interdecadally. In the high NAO state, the westerlies are intense, and the cold continental air they carry off northern North America is warmed by heat liberated from the warm ocean waters they blow across, and that warmed air flows across northern Europe from the southwest. When the NAO is in its low state, the Icelandic low pressure center is displaced far to the south, off Newfoundland, and there is a high pressure center over northern Greenland, causing cold dry polar air to blow across northern Europe, and then westward across the northern subpolar area towards North America, warming on the way by the heat liberated from the ocean to the overlying atmosphere. In this low NAO state, northern Europe experiences much cooler summers and more severe winters than in the high NAO state, while Labrador experiences a milder climate. The bottom two panels of the figure show that the winter storm frequency patterns for the two extreme states of the NAO are quite different, with the northeastern US experiencing more Nor'easters during the low NAO state than during the high.



Jeffery C. Rogers, Ohio State University

The differing winds and the accompanying warmer or cooler periods for northern Europe and northern North America that occur when the NAO index marches from one extreme to the other over periods of a decade or more contribute significantly to the distribution of global temperature change. Comparison of the NAO with a similar climatic index known as the "Pacific-North American" (PNA) index indicates that on decadal time scales there may be coordinated variations throughout the northern hemisphere or even the whole globe.

—*Mike McCartney*

The Bermuda Station S–
A Long-Running Oceanographic Show
Deeper Waters Show Warming Trend

Terrence M. Joyce
Senior Scientist, Physical Oceanography Department

Lynne Talley
Professor & Research Oceanographer,
Scripps Institution of Oceanography

A time series of hydrographic measurements was initiated at Bermuda in 1954 and continues to the present. It began under the banner of the International Geophysical Year (1957–1958) with the scientific support of Henry Stommel of the Woods Hole Oceanographic Institution and William Sutcliffe, director of the Bermuda Biological Station (BBS). The scientists and personnel of the originating institutions have been the most active participants over the years, but the data have been widely used by the international oceanographic community. While other long time series of measurements in the North Atlantic began in association with weather ships, (see "Alpha, Bravo, Charlie" on page 9) only the Bermuda measurements have a strong oceanographic focus.

During the cold winter of 1977, Val Worthington ventured out aboard the National Oceanic and Atmospheric Administration's *Researcher* to study the formation of 18° Water, one of the principal North Atlantic water masses, in the northern Sargasso Sea. In the photo, Worthington is leaving the "hero platform" after launching a Nansen bottle cast.

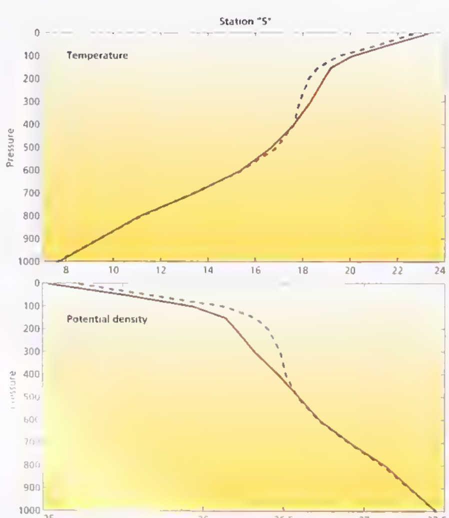
In recent years, large international programs including the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) have provided scientific justification for continuation and expansion of the multidisciplinary Bermuda measurements. As these programs begin to wind down, it is important to recognize the significance of this time series study to understanding of climatic change: These measurements are the principal source of information about subsurface changes in the Sargasso Sea and the subtropical gyre over the past four decades. In early years, the time series was denoted by the attribution "Panulirus," the name of the small BBS research vessel used to carry out the sampling. However, over the years, several other research vessels have serviced the site, and the present practice is to call the time series Station S, in keeping with the convention for many weather ship sites.

In the field of physical oceanography, Station S is not optimally located: There are no major water masses formed there, and the circulation of the subtropical gyre and deep boundary currents only peripherally affect the island. However, its location in proximity to these major North Atlantic circulation features make it ideal for determining larger-scale changes in the basin as they pass by. To make an analogy with the study of automobiles, a researcher might visit various factories to study manufacturing and design changes or just sit by a busy highway and observe the passing traffic—Station S fits the latter category very well.

In the short space available, we wish to discuss some of the changes observed at Bermuda, what they import for the North Atlantic, and possible reasons for their occurrence. We will only look at two "layers" in the water column, the Eighteen-Degree Water and the North Atlantic Deep Water.

Eighteen-Degree Water was first described by WHOI physical oceanographer Valentine Worthington in 1959 as one of the major water masses formed in the northern Sargasso Sea in late winter: It is the principal type of subtropical water found in the North Atlantic. It occurs at depths of a few hundred meters at Station S and is characterized by a layer of nearly constant density having a temperature of about 18° C. While this layer does not form at the surface near Bermuda, it occurs just below the depths of late winter mixed layers near the island and is closely coupled to surface layers found there. The Station S time series has been one of the main barometers (or, more correctly, *thermometers*) of changes in this water mass as it flows

Unfortunately, Worthington's efforts (photo at right) were devoted to a period of minimum production of this water. In contrast to this minimum period in 1976 (denoted by red curves of temperature and potential density), a period of maximum climatological production occurred in 1964 (blue curves). In both cases, the plot shows the annually averaged properties for both calendar years vs. pressure to reduce eddy noise. Note that the underlying thermocline at pressures of more than 600 decibars is similar in both periods: Changes are not induced from below.

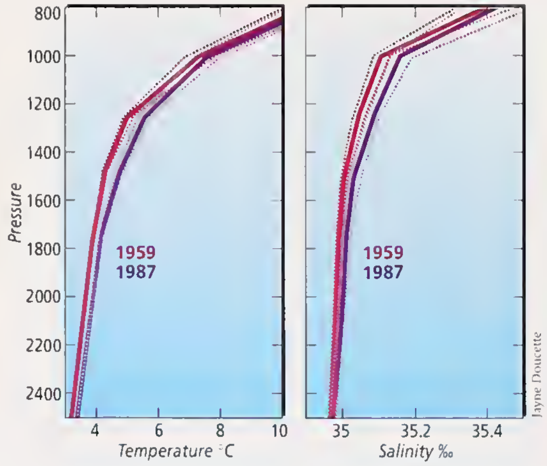


by the island from source regions to the northeast.

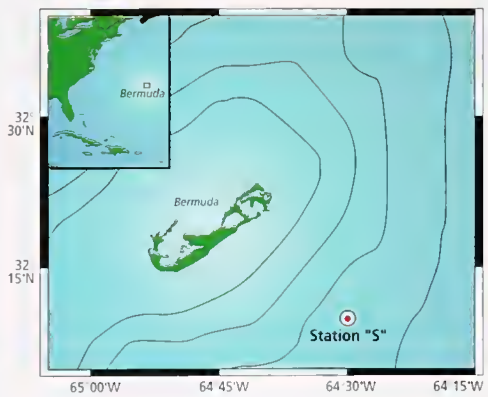
The thickness of Eighteen-Degree Water varies by a factor of two over the course of the current 42-year time series. Temperature and salinity (density) changes also occur over time, and the layer temperature is only approximately equal to 18° C. In years when this Eighteen-Degree Water is produced in large quantities, the surface salinity (but not necessarily temperature) at Station S is high. In poor production years, the surface salinity is low. Thus, long-term changes in this water mass seem to be closely linked with processes that affect the surface salinity. High production periods seem to be recur at intervals of approximately 12 to 14 years. Many of us recall when Worthington convinced the funding agencies to mount a field study of Eighteen-Degree Water, only to find that none had formed that year. We can now see that the climatological minimum of the signal at Bermuda occurred during the mid 1970s when he went to sea! Our study of the processes controlling this variability has not provided a conclusive answer as to why this periodicity occurs and how it is linked to surface salinity—but not temperature—changes, though we believe it must have some connection with changes in atmospheric circulation and precipitation over the subtropical Atlantic Ocean.

At depths of 1,500 to 2,500 meters at Station S, we find another clear signal that is not connected with atmospheric changes over the subtropical gyre. This is a slow increase in temperature over time with a trend that is apparent in records that date to the early 1920s when deep-water oceanographic measurements were first made near Bermuda with accurate reversing thermometers. The long-term trend of this temperature change is at a rate of approximately 0.5° C per century. It is one of the clearest examples of a long-term increase of ocean temperature in the subsurface ocean. That is not to say that the annually averaged temperature in this layer always increases. In fact there are decadal time-scale changes at this depth too, with 1993 appearing to be the coldest in 20 years. Since waters at this depth do not communicate with the surface anywhere in the subtropical gyre, it is the subpolar gyre to the north that is the most likely cause for the variability, if not the trend. Our present studies indicate that long-term changes in the production of Labrador Sea Water are associated with the decadal variability in the deep water at Station S. Since the Station S bottom is at about 3,000 meters, this deep layer is the deepest available in the time series. There appears to be a lag of 5 to 6 years until the Labrador Sea Water signal appears at Bermuda (see "Labrador Sea" article on page 24).

Many of the climate studies that can be undertaken using the time series at Bermuda are ongoing and of greater value as time goes on. This is related simply to the fact that phenomena with time scales of a decade must be studied with time series that span several "events" in order to make any statistically significant statements. The examples given above are marginal in the statistical sense because even the 42-year data set is not long enough—we are always left looking at the most recent years of data and wondering what will come next! For this reason it is essential that the observations continue beyond the lives of some of the large field programs like WOCE and JGOFS, which will end in a few years. Though it is possible that technological advances may enable additional measurements or more cost-effective methods, the Bermuda time series currently offers our principal window into the climate of the subtropical gyre of the North Atlantic.



Deep water changes at Bermuda are illustrated by two contrasting years: 1959 (red curves) and 1987 (blue curves). During the intervening period, the deep water warmed up and became saltier between about 1,200 decibars (or approximately 1,200 meters) and the bottom. At shallower pressures, eddy variability (denoted by the dotted lines on either side of the annual means) obscures any differences. The long-term warming trend at Bermuda can be traced back to 1922, when accurate deep water temperature measurements were made by the Danish ship *Dana II*.



The location of Station S is a short steam southeast from St. Georges' harbor. The smoothed bathymetry is plotted at one kilometer depth increments.

The National Science Foundation has funded the Station S work over the years.

Terry Joyce was a member of the first class admitted to the MIT/WHOI Joint Program in Physical Oceanography 1968. His first cruise, with Henry Stommel aboard Atlantis II *that same year, made a port call in Bermuda, so his Bermuda connection extends far beyond this article. Since completing his doctorate in 1972, he has conducted research at WHOI except for a six-month stint in Germany. Though his research interests have changed over the years, there has always been a strong thread of seagoing work and data analysis/interpretation. For the past eight years, he has served as director of the World Ocean Circulation Experiment Hydrographic Program Office based at WHOI.*

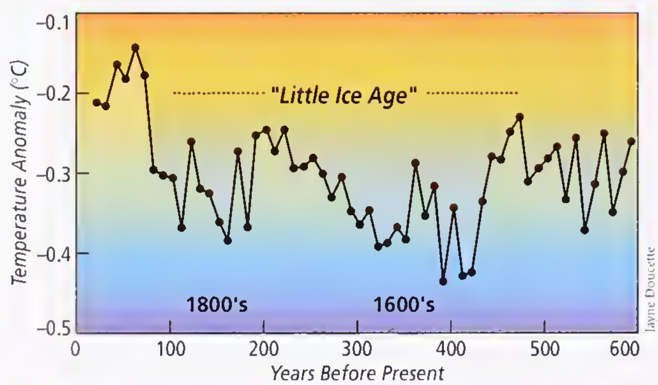
Lynne Talley was also a WHOI/MIT Joint Program student, having begun her graduate career as a large-scale observational oceanographer working on items like Eighteen-Degree Water using the Bermuda record and Labrador Sea Water. She moved into theoretical studies of unstable currents for her degree, completed in 1982, but several years after moving on through a postdoc and beginnings of her research career she found herself squarely back in the intermediate and mode waters of the world, both literally and in print.

Sedimentary Record Yields Several Centuries of Data

The Little Ice Age and Medieval Warm Period in the Sargasso Sea

Lloyd D. Keigwin
Senior Scientist, Geology & Geophysics Department

New Englanders claim a birthright to complain about the weather. As we note that the summer of 1996 was coolest and wettest in recent memory, most of us have already forgotten that summer 1995 was unusually warm and dry. Such variability in weather is normal, yet in historical times there have been truly exceptional events. For example, 1816 is known as the "Year Without a Summer."* During that year, there were killing frosts all over New England in May, June, and August. July 1816 was the coldest July in American history, and frosts came again in September. Crop failure led to food shortages throughout the region. Although the immediate cause of cooling has been ascribed to the volcanic eruption of Tambora in Indonesia the year before, the Year Without a Summer occurred during a time when weather was generally more harsh than today. Persistently harsher weather suggests a change in climate, and the late 16th through the 19th centuries have become known as the "Little Ice Age."



Average summertime temperature over six centuries in the northern hemisphere. Note generally cooler temperatures between 1550 and 1900, the period known as the Little Ice Age. (Data courtesy of Raymond S. Bradley, University of Massachusetts).

The Little Ice Age, and several preceding centuries, which are often called the "Medieval Warm Period," are the subject of controversy. Neither epoch is recognized at all locations around the globe, and indeed at some locations there is clear evidence of warming while others show distinct cooling. One author titled a paper: "Was there a Medieval Warm Period, and if so when and where?" Nevertheless, when data from all Northern Hemisphere locations are considered, the annual average summer temperature proves to be a few tenths of a degree lower during the coldest part of the Little Ice Age in the late 1500s and early 1600s. Various forcing mechanisms have been proposed for such changes, including variation in the sun's energy output, volcanic eruptions, and mysterious internal oscillations in Earth's climate system, but none satisfy all of the data.

Natural climate changes like the Little Ice Age and the Medieval Warm Period are of interest for a few reasons. First, they occur on decade to century time scales, a gray zone in the spectrum of climate change. Accurate instrumental data do not extend back far enough to document the beginning of these events, and historical data are often of questionable accuracy and are not widespread geographically. Geological data clearly document globally coherent climate change on thousand-, ten thousand-, and hundred thousand-year time scales, so why is the record so confusing over just the past 1,000 years? Second, as humanity continues to expand and make more demands on our planet, annual average temperature changes of a degree could have considerable social and economic impacts. Third, as there is widespread agreement among climatologists that changes due to human impacts on atmospheric chemistry will eventually lead to global warming of about two degrees over the next century, it is important to understand the natural variability in climate on the century time scale. Will the human effects occur during a time of natural warming or cooling?

Of several approaches to studying climate on decadal to century time scales, here I will touch on the study of long series of measurements made at sea and the study of deep sea sediments.

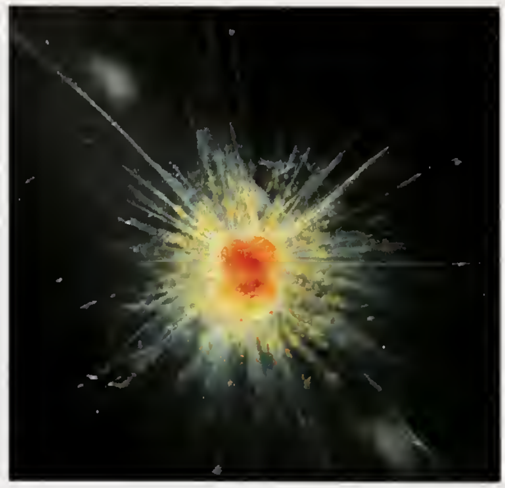
*This phenomenon is described in *Volcano Weather–The Story of 1816, the Year Without a Summer* by Henry Stommel and Elizabeth Stommel (Seven Seas Press, Newport, RI, 1983)

Ordinarily, there is little overlap between these two approaches. Reliable and continuous hydrographic observations rarely extend back beyond several decades, and deep sea sediments usually accumulate too slowly to resolve brief climate changes. However, the northern Sargasso Sea is a region where we have five decades of nearly continuous biweekly hydrographic data (see preceding article), a long history of sediment trap collections to document the rain of particles from the sea surface to the seafloor, and exceptional deep sea cores of sediment. The co-occurrence of these three elements has led to one of the first reconstructions of sea surface temperature for recent centuries in the open ocean.

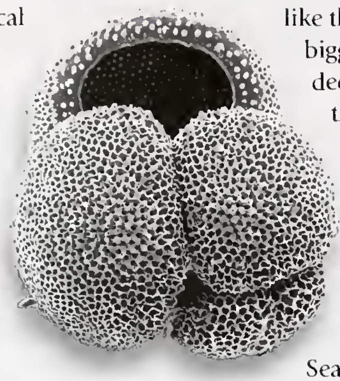
Oceanographically, Station S in the western Sargasso Sea is important because temperature and salinity change there is typical of a large part of the western North Atlantic, and it is exclusively western North Atlantic water that is transported northward and eastward by the Gulf Stream. These are the waters that eventually cool and sink in the Norwegian and Greenland Seas, flowing southward to complete a large-scale convection cell that plays a fundamental role in regulating Earth's climate.

In addition to long time series of hydrographic data from Station S, the site is remarkable for the long series of sediment trap data collected by WHOI's Werner Deuser, beginning in the 1970s. Those traps have recovered nearly continuous samples of the seasonally changing rain of particles that settle from surface waters to the seafloor. An important component of those particles is the calcium carbonate shells of planktonic protozoans known as foraminifera. There are about 30 species of foraminifera, or "forams," and Deuser's investigations have established the seasonal change in species abundance and their stable isotope composition. We now know from these studies that only one species of planktonic foram, *Globigerinoides ruber*, lives year-round at the surface of the Sargasso Sea, and it happens to deposit its calcium carbonate close to oxygen isotopic equilibrium with seawater. This means that *G. ruber* is ideal for reconstructing past changes in the temperature and salinity of Sargasso Sea surface waters, as the figure at right illustrates.

Note that the average sea surface temperature and salinity from near Bermuda display some systematic variability on an annual average basis since 1955. These changes reflect a decade-long variability in the North Atlantic climate regime that is known as the North Atlantic Oscillation (see box on page 13). In this time series, the most severe climate occurred in the 1960s when annual average sea surface temperatures were depressed about half a degree by extreme storminess in the western North Atlantic. Cold, dry winds during winter storms also probably raised surface ocean salinity in the 1960s by promoting increased evaporation. If we had "annual average forams" from the 1960s, their oxygen isotope ratio would look like the time series shown in purple. The biggest climate change of the past five decades could indeed be recorded by the forams.



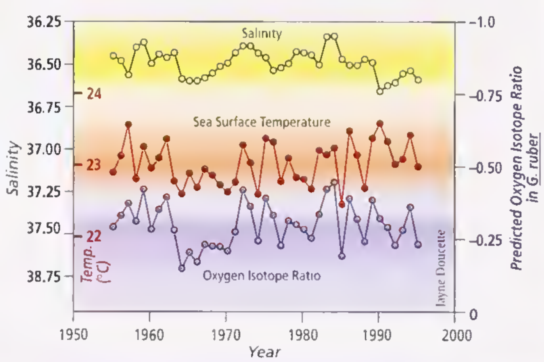
Photos by David Caron



Shells of planktonic animals called formainifera record climatic conditions as they are formed. This one, *Globigerinoides ruber*, lives year-round at the surface of the Sargasso Sea. The form of the live animal is shown above, and its shell, which is actually about the size of a fine grain of sand, at left.

Long before I knew that *G. ruber* was the best possible foram for reconstructing sea surface temperatures, I selected that species for my stable isotope studies because of its consistent abundance on the Bermuda Rise, in the northern Sargasso Sea to the east of Station S. At the time (the early 1980s), the Bermuda Rise was under consideration as a possible site for burial of low level nuclear waste, and it was necessary to know how rapidly and continuously the sediment accumulates. It turns out that because of the action of deep ocean currents, fine-grained clay and silt particles are selectively deposited there, resulting in very high rates of sedimentation. And whether samples are of modern or glacial age, *G. ruber* is consistently present. Much of my work over the past decade has documented the climate changes that occur on thousand year time scales and are preserved in foram isotope ratios and other data from Bermuda Rise sediments.

Until recently, the available data from the Bermuda Rise showed evidence of century- to thousand-year climate change continuing right up to about a thousand years ago, the age of the



Bermuda Station S hydrography shows the oxygen isotope ratio that a foram would have if it deposited its shell in equilibrium with the annual average sea surface temperature and salinity observed since 1954 at Station S near Bermuda. The large decrease in sea surface temperature and increase in salinity in the late 1960s was caused by unusually unpleasant weather those years. (Temperature and salinity data provided by Terry Joyce.)

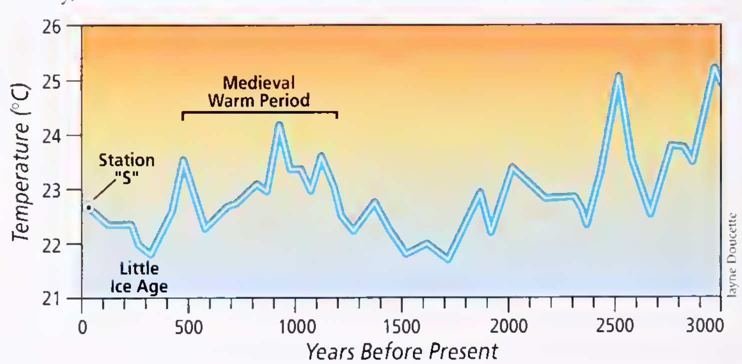
Since 1978, Scientist Emeritus Werner Deuser has collected a nearly continuous suite of deep sediment trap samples at the Ocean Flux Program site near Station S. The Ocean Flux Program traps are shown following recovery aboard the Bermuda Biological Station vessel *Weatherbird II*. The traps were deployed along a bottom tethered mooring at 500, 1,500 and 3,200 meters depths to intercept particles sinking through the water column. Deuser recently passed the leadership of the Bermuda time-series program on to Assistant Scientist Maureen Conte.

sediment at the tops of our cores. Because these samples were recovered with large, heavy tools that free fall into the seafloor, I suspected that they might have pushed away sediments of the last millennium without actually coring them. As a test of this idea, we acquired a box core from the Bermuda Rise (box cores penetrate the seafloor slowly and disturb surface sediments little) and radiocarbon dated its surface sediment at the National Ocean Sciences Accelerator Mass Spectrometry Facility located at WHOI. Results showed that the sediment was modern, and additional dates were used to construct a detailed chronology of the past few millennia. When temperatures were calculated from oxygen isotope results on *G. ruber* from the box core, and when data were averaged over 50 year intervals, I found a consistent pattern of sea surface temperature change (see figure below). The core-top data indicate temperatures of nearly 23 degrees, very close to the average temperature at Station S over the past 50 years. However, during the Little Ice Age of about 300 years ago sea surface temperatures were at least a full degree lower than today, and there was an earlier cool event centered on 1,700 years ago. Events warmer than today occurred about 500 and 1,000 years ago, during the Medieval Warm Period, and it was even warmer than that prior to about 2,500 years ago.

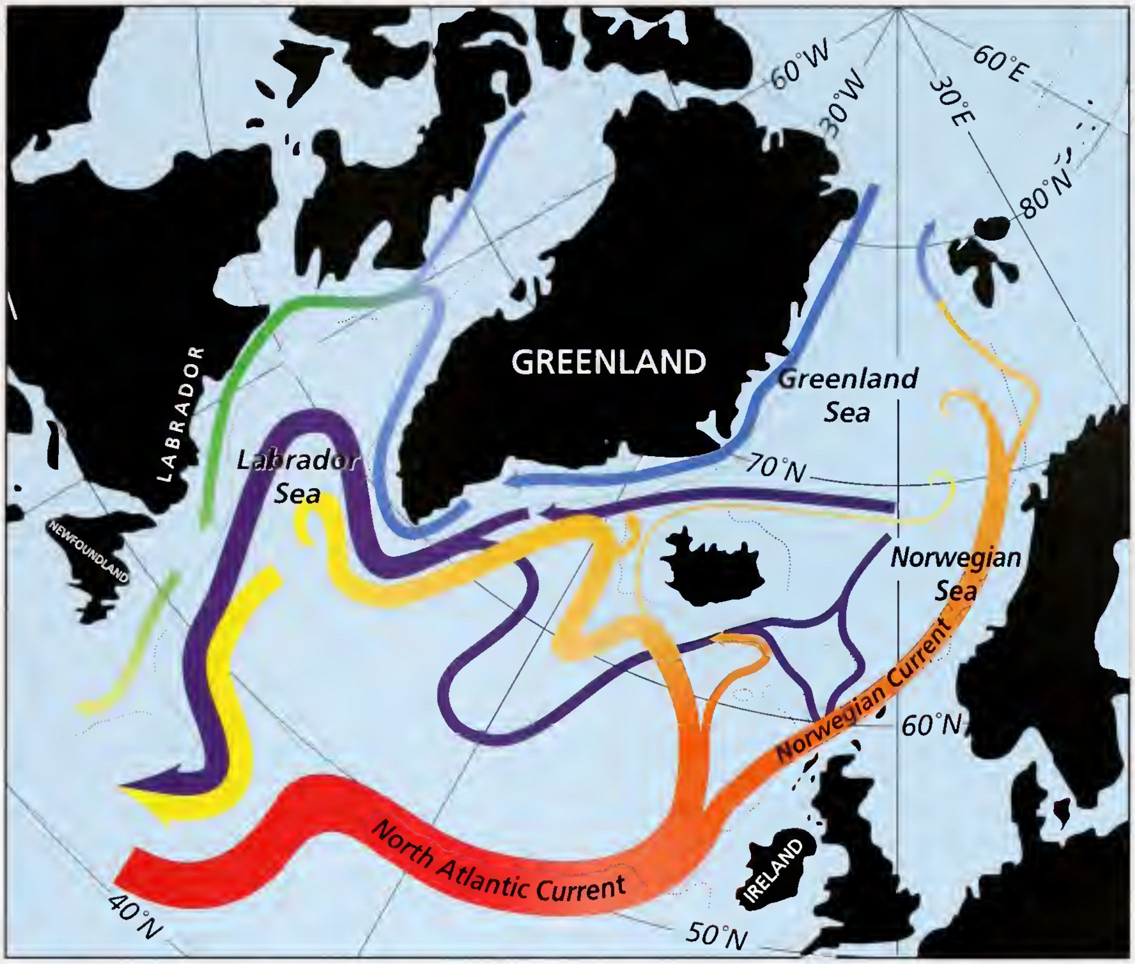
These results are exciting for a few reasons. First, events as young and as brief as the Little Ice Age and the Medieval Warm Period have never before been resolved in deep sea sediments from the open ocean. Because the Sargasso Sea has a rather uniform temperature and salinity distribution near the surface, it seems that these events must have had widespread climatic significance. The Sargasso Sea data indicate that the Medieval Warm Period may have actually been two events separated by 500 years, perhaps explaining why its timing and extent have been so controversial. Second, it is evident that the climate system has been warming for a few hundred years, and that it warmed even more from 1,700 years ago to 1,000 years ago. There is considerable discussion in the scientific literature and the popular press about the cause of warming during the present century. Warming of about half a degree this century has been attributed to the human-induced "greenhouse effect." Although this is not universally accepted, it *is* widely accepted that eventually changes to Earth's atmosphere *will* cause climate warming. The message from the Bermuda Rise is that human-induced warming may be occurring at the same time as natural warming—not an ideal situation. Finally, building on the studies of physical oceanographers and climatologists, marine geologists and paleoclimatologists may use the North Atlantic Oscillation as a model for understanding North Atlantic climate change on longer, century and millennial time scales.

This work was funded by the National Oceanic & Atmospheric Administration's Atlantic Climate Change Program.

We encourage Oceanus *authors to include a bit of humor in the short biographies we request. Lloyd Keigwin claimed to be "a humorless scientist" who doesn't like writing bios, so we asked Eben Franks, a research assistant in Lloyd's lab, to provide some information. Here's what Eben wrote: In addition to running a demanding research program, Lloyd Keigwin is also a Commander in the Navy Reserve. Despite nearly 30 years of seagoing experience he still finds himself subject to seasickness.* [Editor's note: *This is not unusual among oceanographers!*] *Lloyd has been deeply affected by episodes of the popular PBS series "This Old House" and has spent 14 years (and counting) demolishing two perfectly adquate houses in the name of renovation. His limited spare time is consumed with multifarious projects ranging from attempting to convince the Navy to convert a nuclear sub for oceanographic research to casting longing looks at the antique German and British sports cars collecting dust in his barn.*



Estimated sea surface temperature from Station S annual averages and from *Globigerinoides ruber* shell oxygen isotopes averaged at 50-year intervals. Note that the range of sea surface temperature variability on longer time scales is much larger than what has been observed since 1954 at Station S.



Jack Cook

The pathways associated with the transformation of warm subtropical waters into colder subpolar and polar waters in the northern North Atlantic. Along the subpolar gyre pathway the red to yellow transition indicates the cooling to Labrador Sea Water, which flows back to the subtropical gyre in the west as an intermediate depth current (yellow). In the Norwegian and Greenland Seas the red to blue/purple transitions indicate the transformation to a variety of colder waters that spill southwards across the shallow ridge system connecting northern Europe, Iceland, Greenland, and northern North America. These overflows form up into a deep current also flowing back to the subtropics (purple), but beneath the Labrador Sea Water. The green pathway also indicates cold waters—but so influenced by continental runoff as to remain light and near the sea surface on the continental shelf.

North Atlantic's Transformation Pipeline Chills and Redistributes Subtropical Water

But It's Not A Smooth Process And It Mightily Affects Climate

Michael S. McCartney
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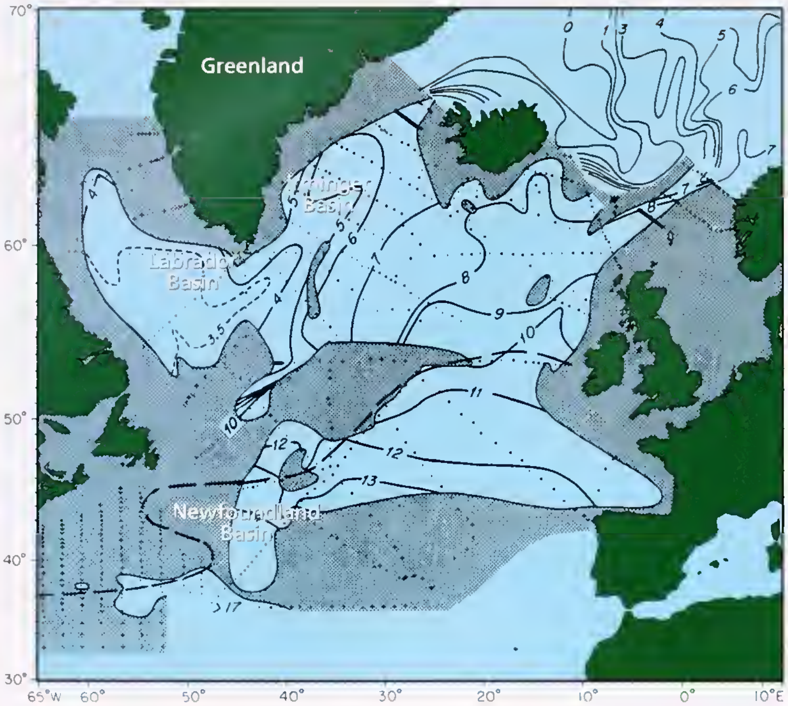
Warm and salty waters from the upper part of the South Atlantic flow northward across the equator and then progress through the tropical and subtropical North Atlantic to reach high latitudes. Beginning with the intense northward flow of the Gulf Stream off the East Coast of the United States, these waters are exposed to vigorous cooling, liberating considerable oceanic heat to the atmosphere. This is the first stage of "warm water transformation" within the North Atlantic, a process that culminates in the high latitude production of cold and fresh waters that return to the South Atlantic in deep reaching currents beneath the warm waters of the subtropics and tropics.

This article focuses on the part of this warm water transformation that occurs northwards of about 45° N, the subpolar realm of the North Atlantic. Here the warm waters brought to the area by the Gulf Stream flow eastward across the basin and then sweep northwards in the eastern Atlantic, continuing to cool, and freshening as precipitation and continental runoff exceed evaporation. This transformation occurs along



Temperature (°C) of the deep mixed layer near the end of winter in the areas where that depth exceeds 200 meters. It is based on hydrographic survey data recorded from 1957 to 1967.

two distinct pathways. The Norwegian Current carries part of the warm water flowing northward past Ireland into the Norwegian and Greenland (Nordic) Seas, while the subpolar gyre carries the rest westwards towards and past Greenland to the Labrador Basin.

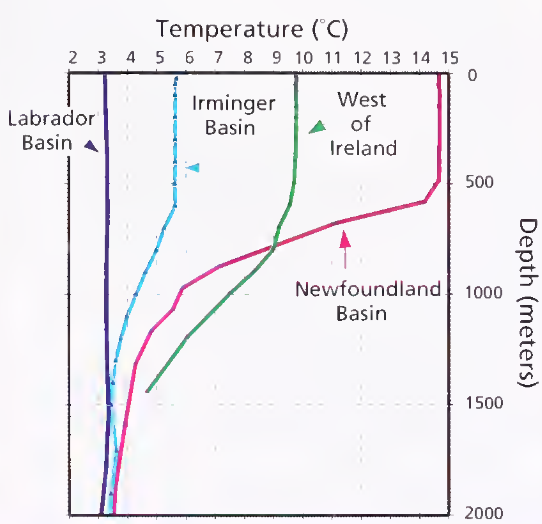
The transformation from warm to colder water is a multi-year process: Wintertime winds cool the surface waters, causing them to convect or vertically overturn and mix progressively more deeply into the cooler waters beneath. This seasonal overturning creates large volumes of vertically homogenized water, called mode waters. In summer, the sun heats the surface waters, forming a cap of warmer water that effectively isolates the mode water from contact with the atmosphere. Surface cooling in the following winter removes the cap, and reexposes the mode water, which then undergoes another round of winter cooling in which it gains more thickness. The mode water thus cools and thickens progressively through consecutive annual reexposures to the atmosphere as it simultaneously flows counterclockwise around the subpolar gyre.

In winter data the seasonally exposed mode waters form a smoothly varying ring of progressively colder and more deeply convecting waters (see figure at left). Estimates of flow speeds in the subpolar gyre suggest a transit time of about a decade for a parcel of water that enters the transformation pipeline east of Newfoundland with a temperature of 12° to 14° C, travels counterclockwise, and emerges from the pipeline in the Labrador Basin at temperatures colder than 4° C. The figure below left illustrates the great thickness of the regional convection in this mode water ring with temperature/depth profiles from the Newfoundland Basin where the ring begins, west of Ireland in the northward flow of the eastern subpolar gyre, in the Irminger Basin east of Greenland where flow is westward, and in the Labrador Basin where the mode water ring ends.

The process of heat liberation from ocean to atmosphere by water flowing along the pipeline acts as a regional radiator, particularly for northern Europe where the westerlies carry the heat extracted from the ocean. There is considerable evidence for interdecadal variability in this climate process. Our first evidence comes from the Labrador Sea where deep wintertime convective overturning constitutes the last stage of cooling along the transformation pathway and vertically homogenizes the water column to depths sometimes exceeding 2,000 meters, creating the so-called Labrador Sea Water (coolest profile in figure below left).

The following article discusses the history of Labrador Sea Water (LSW). The figure on the opposite page shows the LSW temperature record overplotted with a smoothed version of the North Atlantic Oscillation index, an expression of the relative strength of the atmospheric westerlies (see box on page 13). The LSW temperature history shows a long period of warming from the 1930s to 1971 followed by cooling from 1972 to 1993, culminating in the 1990s with the coldest, freshest, and thickest LSW ever observed. This cooling trend, however, was interrupted by a brief warming in the late 1970s and early 1980s. Thus the first piece of evidence for climate change in the warm water transformation system is that the system's end product, LSW, which in the figure opposite maps in winter 1962 as 3.3° C, shows interdecadal variability with temperatures as warm as 3.5° C in 1970, compared to as cold as 3.1° C forty years earlier and as cold as 2.7° C twenty-three years later.

Several agents interact to produce LSW. The



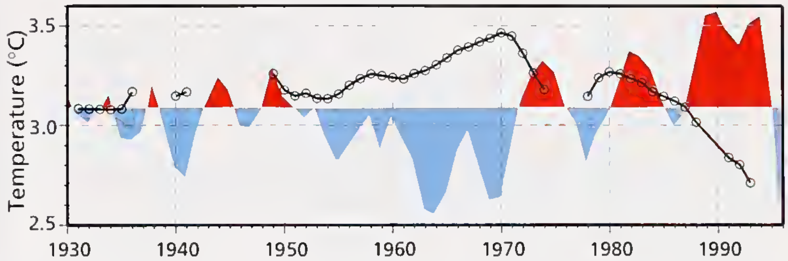
Examples of the variation of temperature with depth from the stations used for the figure above.

LSW within the Labrador Basin has a "residence time." The total volume of LSW is only partially replaced each year through the addition of transformed warm water and export of LSW from the Labrador Basin to the rest of the North Atlantic. To visualize this, imagine the Labrador Basin as a jacuzzi. Water is supplied to the tub at some temperature and at some rate, is well stirred and mixed in the tub, and that mix is drained away at a rate that matches the supply rate. The residence time is the volume of the tub divided by the rate of supply and is a measure of the time a given parcel of water spends in the tub before going down the drain, and thus is the average time the water in the tub loses heat to the overlying colder air. The temperature of the mixed water in the tub depends on the temperature history of the warm water being fed into the tub, the rate of that water supply, the residence time, and the rate of heat loss from the tub to the air above it. LSW temperature similarly depends first on the temperature history of the product emerging from the warm water transformation pipeline into the Labrador Basin plus the rate of that flow, and second on the history of the heat exchange between the Labrador Basin waters and the overlying atmosphere and surrounding ocean (sort of an uninsulated tub!). Other factors can influence such histories: Ice atop the jacuzzi alters how its tub temperature evolves; similarly, sea ice and upper ocean freshwater circulation can modify convective cooling in the Labrador Basin.

The second kind of evidence for climate change signals in the northern North Atlantic comes from sea surface temperature (SST) data. While such data ultimately represents just the skin of the ocean, it has the advantage of much higher data density in space and time than subsurface data, for it can be collected from ships of opportunity without requiring a specialized research vessel and in recent decades can be remotely sensed from satellites. SST is a quantity of great importance in heat exchange with the overlying atmosphere. With some care in interpretation, it can be linked to conditions beneath the sea surface. Clara Deser's article on page 11 discusses the overall regional northern North Atlantic SST history. Subpolar and northern subtropical SSTs were overall anomalously warm in the 1950s and 1960s. Winter SST data reveals that this general warmth involved warm SST anomalies propagating with the oceanic circulation. The figure on the next page documents the birth in 1951 of a warm winter SST anomaly east of Newfoundland (red patch) and traces its progression around the subpolar gyre in subsequent winters through 1968. In the late 1960s, a cold SST area develops in the subtropics near 40° N, propagates into the subpolar gyre with maximal extent in the mid 1970s, fades around 1980, and reestablishes in the mid 1980s. We call these SST "anomalies" because they represent departures from the long-term local temperatures.

Comparison of this interdecadal progression of warm and cold SST anomalies to the LSW temperature history shows provocative parallels: The post-World War II LSW warming trend occurs while the warm SST anomaly travels along the transformation pathway. The LSW cooling period beginning in 1971 coincides with substantial cold SST areas in the subpolar gyre—but that general coldness is interrupted by warmer SST anomalies in 1980–81, when the LSW cooling trend was also interrupted. Thus the second piece of evidence for climate change in the warm water transformation system: There are significant interdecadal winter SST anomalies in the subpolar gyre as a whole and in particular moving along the warm water transformation pathway. Periods of relatively warm SST anomalies along the transformation pipeline correspond to periods when LSW warmed, and periods of relatively cold SST anomalies to periods when LSW cooled. These observations suggest that the supply of transforming warm water to our Labrador Basin jacuzzi was running warmer in the 1950s and 1960s compared to the succeeding decades. To further that idea, a link between SST anomalies and the subsurface water undergoing transformation is needed.

The third kind of evidence for variability in the northern North Atlantic climate system comes from subsurface hydrographic data, which allow us to link warm and cold winter SST phases to variability in the mode water distribution. The figure on page 23 shows temperature and salinity difference fields at 400 meters in the northern North Atlantic. This depth falls in the winter convection range of the mode water along the warm water transformation pathway (but below the depth of the seasonal warming cap), and thus periods of warm or cold 400-meter temperature correspond to the array of isotherms of the top figure on page 20 shifting counterclockwise or clockwise, respectively. The fields in the figure on page 23 are constructed by subtracting the temperatures for one time period from the preceding time period and mapping the difference. Our

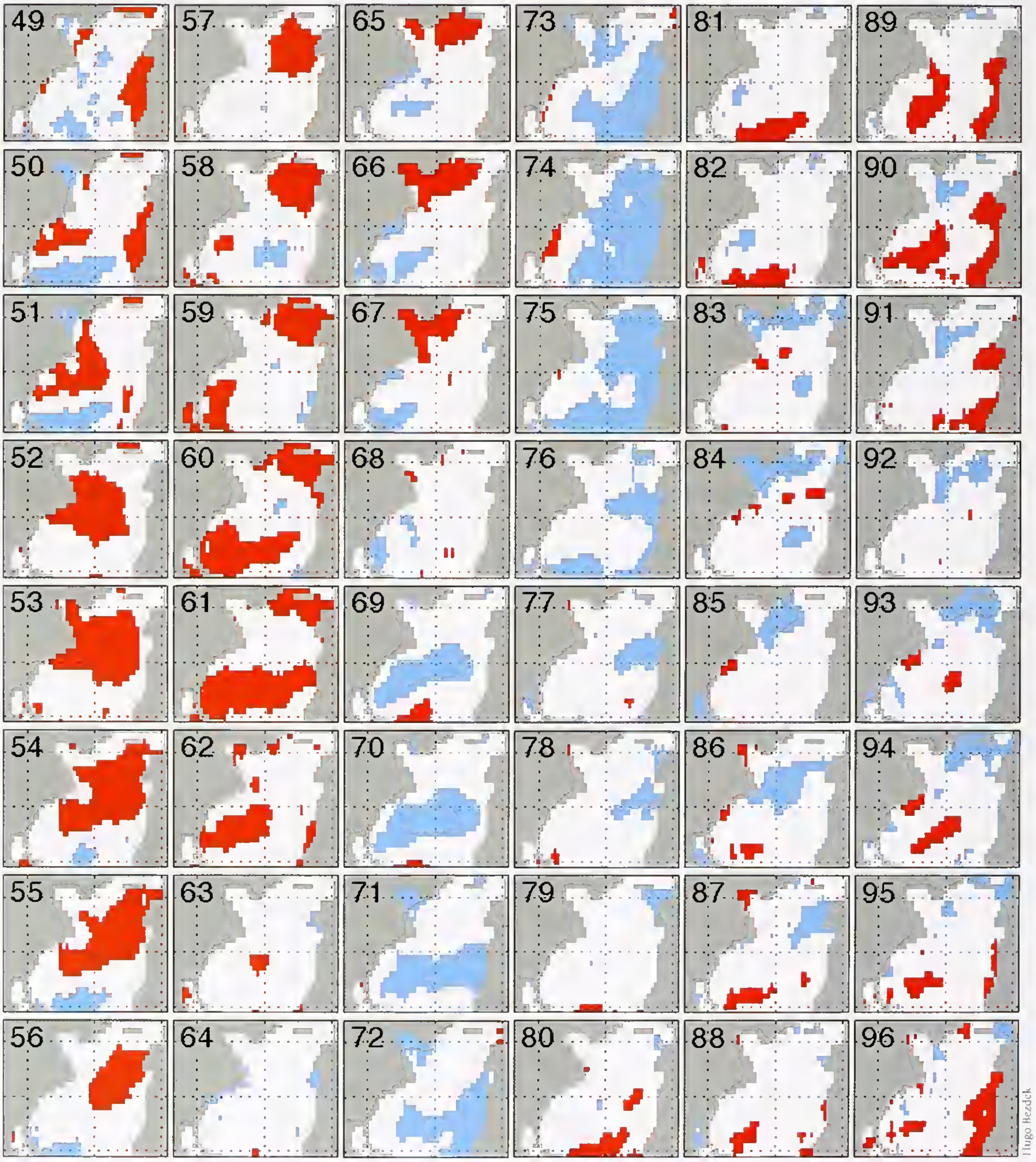


The history of temperature (circles and black line) of the Labrador Sea Water convecting in the central Labrador Basin to depths sometimes exceeding 2,000 meters. This is compared to the interdecadal march of an index of the North Atlantic Oscillation, with the reds indicating the high index periods of strong westerlies, and the blues the low index periods of weak westerlies. See the North Atlantic Oscillation box on page 13 for an explanation of the high and low states of the "NAO". The NAO index plotted here is formed from the sea-level pressure difference between the subtropical Azores high pressure center and the subarctic low pressure center near Iceland. The authors thank James Hurrell (National Center for Atmospheric Research) for the latest updates of NAO index data.

search for systematic warming/cooling is reasonably successful for the period after World War II, but breaks down in more recent years because less data was collected in the 1980s. Although more measurements have been made in the 1990s, data generally takes several years to become available from data archive centers. The figure on page 23 shows that almost the entire subpolar region at 400 meters warmed in 1958–65 compared to 1950–57. Thus as the warm SST anomaly traversed the transformation pipeline, the deep winter convection temperatures were warmer than usual.

This warming trend continued in the more northern area through 1966–72, but reversed to cooling in the upstream part of the transformation pipeline between Newfoundland and Ireland. We attribute this to an influx into the pipeline of abnormally cold subtropical waters—which are visible in SST in 1969 to 1972—and to winter convection beginning to run abnormally cold. In the final panel of the figure on the opposite page we see that cooling has taken over almost everywhere, consistent with the continued propagation of the cold SST disturbance along the pipeline. Thus we find evidence that the supply pipeline of our oceanic jacuzzi has slow interdecadal variations of temperature, and that its warming and cooling trends are in phase with the trends of the jacuzzi tub water, the LSW.

So far, what we have described are several aspects of interdecadal variability of upper ocean signals and their linked behavior. Our fourth kind of evidence for changes in the northern North Atlantic returns to the LSW temperature history and the overplotted NAO index recorded

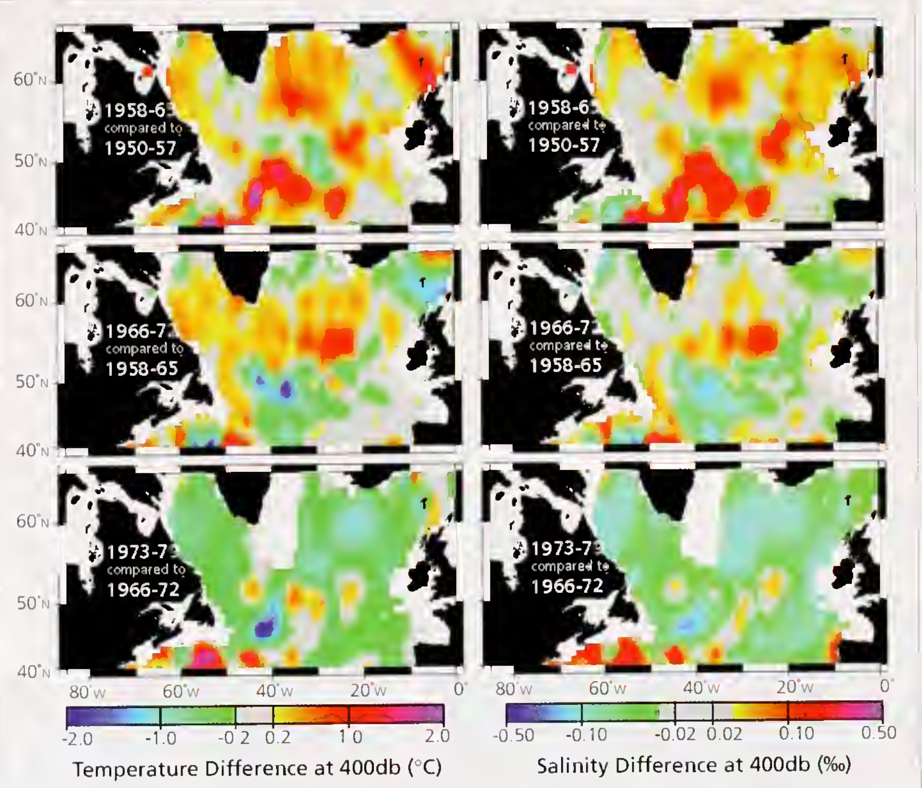


A time series of maps derived from winter SST measurements from 1949 to 1996. Pronounced warm SST anomalies are indicated by red and pronounced cold SST anomalies by blue.

in the figure on the previous page. This index registered high values around 1950, declined to very low values in the late 1960s, then rose to very high values again in the early 1990s, indicating an interdecadal cycle of the basic index of the North Atlantic atmosphere's mid-latitude climatic state. Dan Cayan of the Scripps Institution of Oceanography has shown that a high NAO index tends to enhance liberation of heat from ocean to atmosphere over the Labrador Basin while a low NAO index tends to diminish it. Extrapolating his results to this interdecadal time scale, the 1950s and 1960s, with NAO index declining, correspond to progressively reduced cooling over the Labrador Basin. Thus not only was our jacuzzi supply pipeline running warm, but less heat was escaping from the jacuzzi tub, that is, from the Labrador Basin to the overlying atmosphere. Thus the weakening westerlies reinforced the warming trend for LSW. Conversely, in the period of strengthening westerlies in the 1970s and 1980s, not only was the transformation pipeline running cold, but the loss of heat from the ocean to the atmosphere over the Labrador Basin was progressively enhanced, reinforcing the LSW cooling trend.

What we have described is a first step in this sort of climate change work: establishing interdependence in the climate system's physical properties. The second phase is even more difficult and challenging than the first: How are those properties linked or physically coupled? Which "are in charge," so to speak? Is the ocean a passive participant, merely responding to atmospheric forcing changes, or do feedbacks from the ocean to the atmosphere force evolution of the atmospheric system's climatic state? Certainly, there is a large heat release to the atmosphere involved in maintaining the mean state of climate in the North Atlantic region, and it makes sense that changes in the warm water transformation system ought to lead to changes in the overlying atmosphere. But the link between midlatitude SST anomalies and their potential forcing of climate change signals has been surprisingly elusive to theory and modeling efforts, and is, in fact, one of the primary unresolved issues in climate change research. You might say it is our "missing link."

Continued measurements are essential to further progress in unraveling the signals and their underlying physics, both to monitor the evolution of the system and to sharpen understanding of the physics of specific elements. Two of us (McCartney and Curry) took the Institution's Research Vessel *Knorr* to the subpolar gyre in fall 1996 to begin a concentrated two-year international effort directed at understanding the seasonal cycle of the warm water transformation pipeline of the eastern subpolar gyre.



Maps of temperature and salinity changes for successive time periods at a depth near 400 meters in the northern North Atlantic. Reds and yellows indicate that the later of the two periods is warmer or saltier, while blues and greens indicate the later period is cooler or fresher. Gray areas indicate small salinity and temperature change. White areas indicate a lack of data.

Mike McCartney came to the Institution in 1973 with a mechanical engineering/ fluid mechanics degree, and the late Val Worthington supervised his on-the-job training in oceanography. His interests in the formation of higher latitude water masses and their subsequent circulation have taken him all over the world's oceans, and he has been doing it long enough to personally observe the climatic evolution of his favorite water masses. His goal is to plan longer and more frequent cruises on his sail boat, where, unlike on research vessels, fancy equipment can be restricted to GPS navigation.

Ruth Curry came to Woods Hole in 1980 as a volunteer at-sea watchstander and "mud washer." Sixteen years—and many cruises —later, the sea still holds its allure, but Ruth now sails as a Chief Scientist, measuring changes in water mass properties and ocean circulation in search of pieces to the global climate puzzle. Parenthood has changed her perspective somewhat—going to sea used to mean no sleep, long hours, lousy food, and unpleasant working conditions, she says. Now it means getting more sleep than normal, having to think only about work, and getting all your meals cooked for you—a vacation!

Hugo Bezdek joined the Scripps Institution of Oceanography in 1970 following completion of a degree in physics. After four years of projects in underwater acoustics and air-sea transfer, he became a program manager at the Office of Naval Research (and ceased, he says, doing the actual work). In 1980, he moved to another administrative position as Director of AOML, a NOAA research lab that focuses on climate-related oceanography and meteorology. "During the last few years," he reports, "I have realized the error of my ways and have been struggling mightily to redress past sins and return to honest work once again. With the help of generous people such as my co-authors, perhaps such an eventuality is possible."

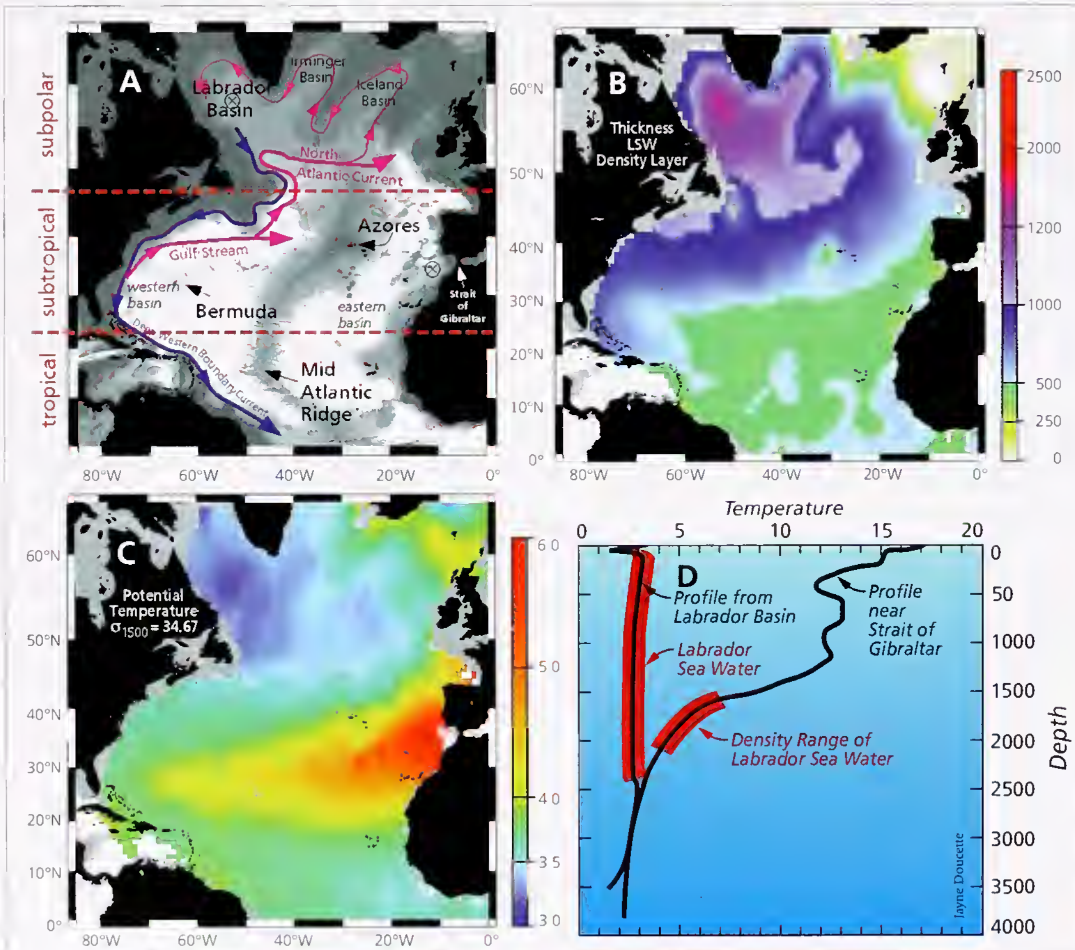
Labrador Sea Water Carries Northern Climate Signal South

Subpolar Signals Appear Years Later at Bermuda

Ruth G. Curry
Research Associate, Physical Oceanography Department
Michael S. McCartney
Senior Scientist, Physical Oceanography Department

Changes in wind strength, humidity, and temperature over the ocean affect rates of evaporation, precipitation, and heat transfer between ocean and air. Long-term atmospheric climate change signals are imprinted onto the sea surface layer—a thin skin atop an enormous reservoir—and subsequently communicated to the deeper water masses. Labrador Sea Water is a subpolar water mass shaped by air-sea exchanges in the North Atlantic. It is a major contributor to the deep water of the Atlantic, and changes of conditions in its formation area can be read several years later at mid-depths in the subtropics. Mapping these changes through time is helping us to understand the causes of significant warming and cooling patterns we have observed at these depths in the North Atlantic and links the subtropical deep signals back to the subpolar sea surface conditions.

Labrador Sea Water (LSW) is the end-product of the transformation process, described in the preceding article, that modifies warm and saline waters through heat and freshwater exchanges with the atmosphere. In the last stage of this transformation, deep wintertime convection occurs in the Labrador Basin between North America and Greenland where strong westerly winds cool the surface waters, making them denser than the underlying deep water. Convection occurs when the denser surface waters sink and mix with the deep water



A: Structure of the North Atlantic basins is defined by bathymetric contours (2,000, 3,000, and 4,000 meters) progressively shaded gray. The Mid-Atlantic Ridge separates the western and eastern basins. The dominant currents at mid depths (near 1,500 meters) are approximated by the pink lines (bringing relatively warm water northward) and the blue lines (transporting cold waters southward).
B: Thickness in meters of the density layer corresponding to the Labrador Sea Water (LSW).
C: Temperature, in degrees centigrade, of a density surface in the middle of the LSW layer. These maps highlight the geographical distribution of the Labrador Sea Water and the Mediterranean Outflow water masses that mix to produce Upper North Atlantic Deep Water.
D: Temperature profiles from the Labrador Basin and the Mediterranean Outflow region (locations are shown by x in panel A). Green shading denotes the density layer that is mapped in panel B for each profile.

to produce the cold, thick, and homogeneous LSW water mass.

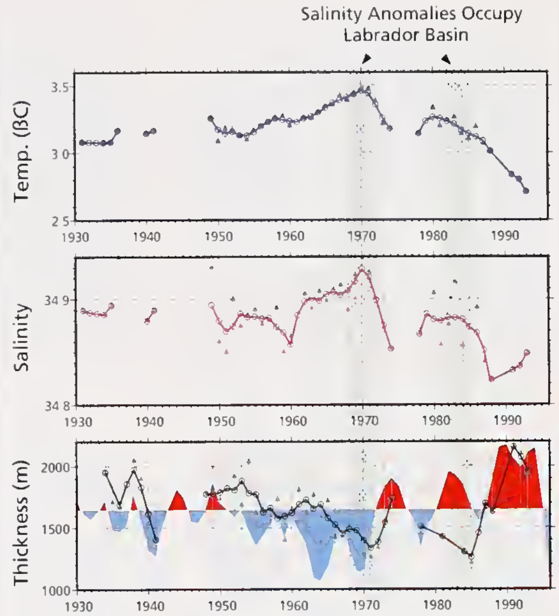
In the figure at left (top right panel) we use the thickness of the LSW mass to indicate its source region and the pathways along which it spreads. In the North Atlantic, the LSW is very thick, but as the circulation carries it away from the Labrador Basin, mixing with other thinner water masses progressively erodes its thickness. The intense pink colors of the two righthand figures opposite indicate thicknesses exceeding 2,000 meters in the LSW formation area. Purple colors show somewhat thinner LSW spreading northeast into the Irminger Basin east of Greenland, eastward via the North Atlantic Current into the Iceland Basin, and southwestward along the western boundary into the subtropical basin.

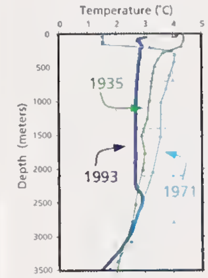
In this, the cold, fresh and thick LSW contrasts sharply to its neighboring North Atlantic water masses of the same density. A cool, salty, but very thin layer of Iceland-Scotland Overflow Water occupies the northeast corner of the map as the yellow-white colors on both thickness and temperature maps. The warm, very salty, and thin Mediterranean Overflow Water is represented by the green (thickness) and yellow-red (temperature) tongues extending across the North Atlantic from its source region at the Strait of Gibraltar. Recirculations associated with the Deep Western Boundary Current, the Gulf Stream, and the North Atlantic Current (an extension of the Gulf Stream) mix the LSW and Mediterranean waters, creating the intermediate thicknesses (blue colors) and temperatures (green colors) between the two sources. The water mass that results from the mixing of LSW and Mediterranean Overflow Water is called the Upper North Atlantic Deep Water; it represents one of the major elements exported into the South Atlantic as part of the global conveyor belt (see inside front cover).

The 500-meter thickness contour roughly separates the areas where LSW strongly influences this layer from regions where Mediterranean Overflow characteristics predominate and shows that these LSW influences can be traced southwards along the western boundary all the way to the tropics. Although the top of the LSW layer is at the sea surface in its subpolar source region, in the subtropics it is isolated from contact with the atmosphere and occupies depths between 1,200 and 2,200 meters.

LSW properties—temperature, salinity, and thickness—have changed significantly through time, and continued measurements in the Labrador Basin since the 1950s enable us to create the time series shown in the figure above right. This record shows a general warming from the 1930s to 1971, followed by a cooling trend that persists to the present. Thickness of the LSW layer is directly related to the intensity of wintertime convection, with strong convection producing a thick layer and weak convection resulting in a relatively thin layer. Thick conditions in the 1930s, 1950s, 1970s, and 1990s indicate periods of strong convection and loosely correlate to cooler, fresher LSW conditions. Note the abrupt end to the 1950s and 1960s warming, increasing salinity, and thinning with the onset of strong convection in 1972. This cooling, freshening, and thickening event, however, is interrupted by a period of weak convection in the early 1980s. Then, by 1987, the return of strong convection culminates in the coldest, freshest, and thickest conditions ever measured. The figure at far right contrasts vertical temperature profiles from the warm and cold phases of LSW to emphasize the extraordinary cooling of the Labrador Basin's water column over the past 25 years. Note that this cooling has chilled the LSW beyond its previous cool state more than 60 years ago, in the 1920s and 1930s.

Two factors principally determine LSW property history: the strength of the winds and the periodic appearance of freshwater anomalies at the sea surface. The westerlies, which blow cold, dry air from Canada across the Labrador Basin, are a significant factor in determining the depth of Labrador Basin wintertime convection. An increase in wind strength removes more heat from the surface waters and deepens the extent of the convection. This also results in a cooler overall LSW, since the increased heat loss at the sea surface is distributed downward as the water column convects. The relative strength of the westerlies is represented by the North Atlantic Oscillation (NAO) index. (See NAO Box on page 13. The NAO index is defined in the figure caption on page 21.) Overplotted on the thickness axis in the figure above, the NAO index (shaded





Left, time series of Labrador Sea Water properties in its source region. Thickness is the vertical distance (meters) between two density surfaces that bracket the Labrador Sea Water. The North Atlantic Oscillation index has been overplotted on the thickness axis with high index shaded red and low index blue. Years in which surface salinity anomalies occupied the Labrador Basin are shaded green. Above, depth profiles of temperature for three different years contrasting the Labrador Sea Water temperature in its cool period before World War II (1935), the peak of warming (1971), and at its coldest point (1993).

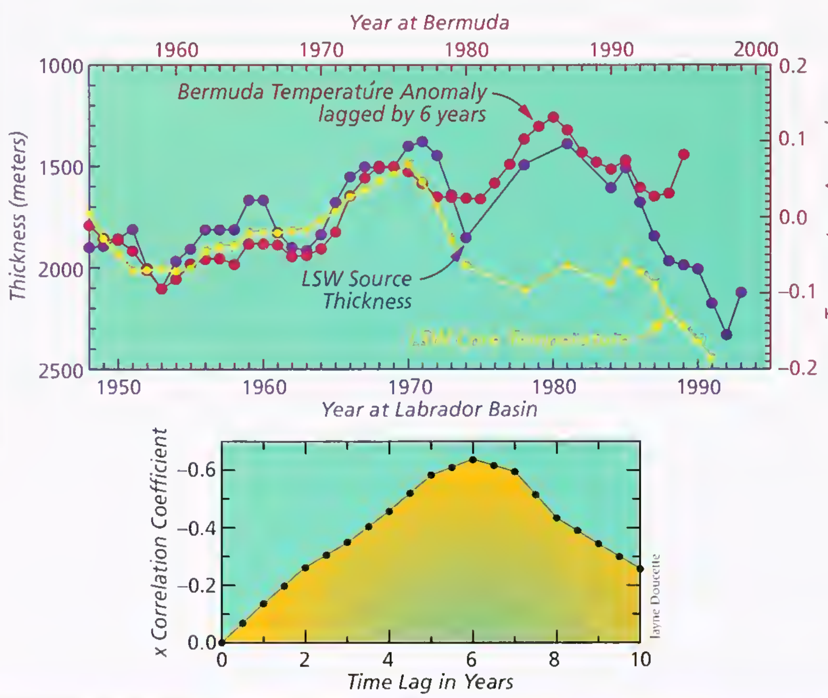
red for high, blue for low) shows trends similar to the LSW thickness: declining NAO index and thinning LSW from the 1950s to 1970, a pulse of strong westerlies and LSW thickening in the early 1970s followed by weak westerlies and thin conditions in the late 1970s, then extremely strong westerlies (high NAO index) and thick conditions in the 1990s. Notice also in the figure on the previous page that LSW temperature is warming during low NAO periods and cooling during years of high NAO. Thus the atmospheric climate signal becomes imprinted on the LSW thickness and temperature.

The thin LSW layers of 1967–72 and the early 1980s correspond to buildups of extremely low surface salinity conditions, which resulted in low surface densities. Because this surface water required extraordinary cooling to make it denser than the underlying water, it completely inhibited convection in the Labrador Basin. These two events, referred to as the "Great Salinity Anomaly" and the "Lesser Great Salinity Anomaly," eventually moved around the subpolar gyre (see "If Rain Falls" on page 4). The first Great Salinity Anomaly occupied the Labrador Basin during a time of low NAO index when weak winds would have reduced the convection depths anyway. However, the Lesser Great Salinity Anomaly hindered convection in the early 1980s, which resulted in a thin LSW source despite strong westerlies associated with a relatively high NAO index. Both anomalies ended with a strong increase in convection and a downward mixing of the freshwater cap, which dramatically lowered the LSW core salinity and temperature.

The subpolar LSW, carrying the imprinted climate signals, enters the subtropics along two principal pathways: The deep western boundary current transports LSW from the Labrador Basin to the Caribbean Islands, and the Gulf Stream and North Atlantic Currents carry it from the western boundary out into the interior of the ocean. The LSW in these flows is strongly stirred and mixed by current and eddy action along these pathways and in the ocean interior. In the figure on page 24, the basin-scale, deep-water properties thus represent a blending of the LSW influence with other influences, principally the Mediterranean Overflow Water. The resulting blended water mass, known as the Upper North Atlantic Deep Water (UNADW), exhibits a temperature history that we can now relate to variations in LSW source properties. This link was previously obscure because the subtropical UNADW temperature signal is more strongly influenced by the LSW *thickness* history than by the LSW *temperature* history. Furthermore, the time the ocean requires to transport and mix the LSW into the subtropical UNADW introduces a time delay to the link between these signals.

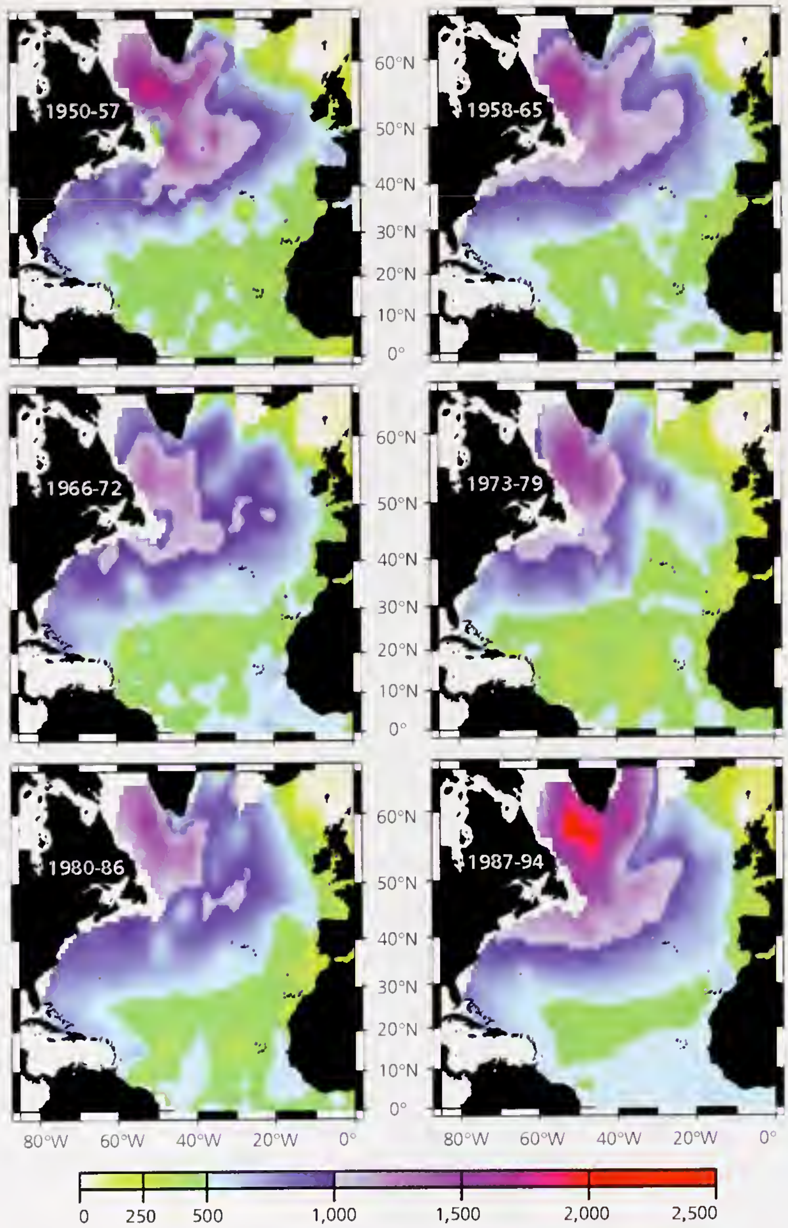
The temperature of the subtropical mid depths (1,000 to 2,500 meters) has generally warmed since the 1950s. The figure below left (red curve) shows this warming trend using a long time series measured at Bermuda and a recent analysis of its thermal structure by Terry Joyce and Paul Robbins (see "Bermuda's Station S" on page 14). When a time lag is applied to the Bermuda signal, its temperature is remarkably similar to the LSW thickness (blue curve), while the subpolar LSW temperature signal (yellow curve) diverges after 1975. Correlation between the subtropical temperature and subpolar thickness signals is greatest at lags of five to six years and implies that when subpolar convection is strong—and the LSW layer is thick—the subtropics follow five to six years later with cooler temperatures at mid depths. Conversely, weak convection and a thin LSW layer is followed by warmer subtropical temperatures approximately six years later.

To place this relationship into a geographic context, the figure opposite maps the thickness of the LSW density layer in six different time frames,



Temperature changes recorded in the 1,500 to 2,500 meter layer near Bermuda. The top plots show time series of Bermuda temperature anomaly (red curve) lagged by 6 years, thickness of the Labrador Sea Water layer (blue curve) in its formation area, and temperature of the LSW core (green curve). The lower plot shows a lagged correlation analysis for Bermuda temperature and Labrador Sea Water (LSW) thickness, which is highest for lags of 5 to 7 years. The authors' interpretation is that subpolar thickness anomalies result in variability of the volume of LSW entering the subtropics. A large volume of LSW shifts the balance of influence between LSW and Mediterranean Outflow towards LSW. When the LSW is thick, Bermuda sees colder (and fresher) conditions about 6 years later, while a thin LSW source results in stronger Mediterranean Outflow influence and Bermuda sees warmer (and saltier) conditions after about 6 years.

each spanning about 7 years and chosen to represent phases of LSW source variation. As noted above, the thickness of the LSW layer in its subpolar formation area changes through time as the convection intensity varies: The Labrador Basin LSW source is thick in the first two time frames, extremely thin in 1966–72 and 1980–86 (a thick pulse in 1973–79 separates these two periods), and grows to extreme thicknesses in the final time frame. Away from the source (near the western boundary east and south of Newfoundland and east of New England), the layer is noticeably thin in the 1970s and 1980s, but robustly flooded with LSW in the 1950s and 1990s. Over the rest of the subtropics (north of 10° latitude), the LSW layer thickness changes most in the fourth time frame (1973–79) when the Mediterranean Overflow Water characteristics (green colors) are extended northwards in the eastern basin and westwards in the western basin. Compare the areas around the Azores and south of Bermuda in each panel to see this change.



Thickness of the LSW density layer for six consecutive time periods.

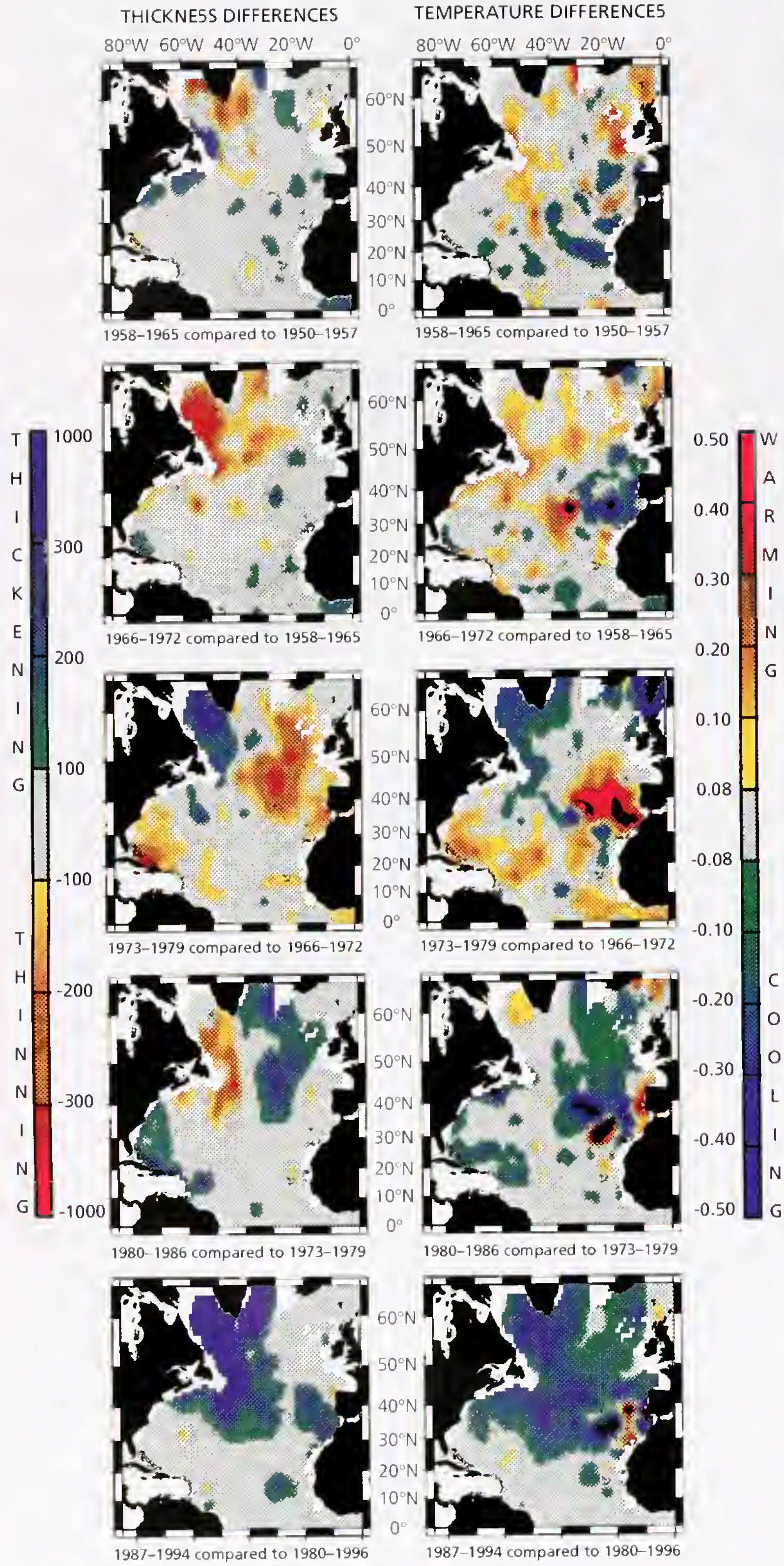
In order to visualize the impact of LSW temperature and thickness anomalies (changes in temperature and thickness) on the subtropics, the figure on the next page maps the temperature and thickness *differences* in one time frame compared to the previous time frame for each period in the figure at right. The patterns of anomalies show large areas where thickness changes correspond to temperature changes—where the layer thins, temperatures grow warmer, and where the layer thickens, temperatures are cooler—and delineate where LSW exerts a strong influence. These patterns also show consecutive instances where temperature and thickness anomalies of one color first appear in the Labrador Basin, rather quickly move southward and eastward with the western boundary current and North Atlantic Current, and then, one time frame later, anomalies of the same color appear in both the western and eastern subtropical basins. The subtropical deep water anomalies appear to lag behind the subpolar LSW signal by five to seven years as the lagged correlation of the Bermuda data suggests.

The subtropical temperature anomalies are large compared to the subpolar temperature anomalies. Because a signal weakens as it moves away from its source, these subtropical signals cannot be simply the advected subpolar temperature anomalies. Rather, the time-delayed subtropical response to LSW source variability represents the slow adjustment of the subtropical deep water to the waxing and waning of LSW strength so clearly visible in the figure above. The thicker the LSW, the stronger its role in mixing with Mediterranean Overflow water, and this is manifested as an eastward and southward erosion of the influence of the Mediterranean Overflow Water on the subtropical deep water. The time needed for the LSW to circulate and mix into the subtropical basins results in a delayed appearance of the response. When the LSW is thinner than normal, the Mediterranean Overflow Water exerts more influence, and this appears as a westward and northward extension of the thin, warm, and salty characteristics.

Understanding the nature of the subtropical temperature variations and knowing that the subpolar convection has been extremely strong from 1988 to 1995 enables us to predict that the subtropical mid depths will continue to cool through the 1990s. Tracing the extremely cold, fresh, and thick signal that is now invading the subtropics (quite pronounced in the bottom panels of the figure on the next page) will provide us with valuable information concerning the timing and geography of the complex mid-latitude circulation system whose end product, the Upper North Atlantic Deep Water, is exported to the southern ocean.

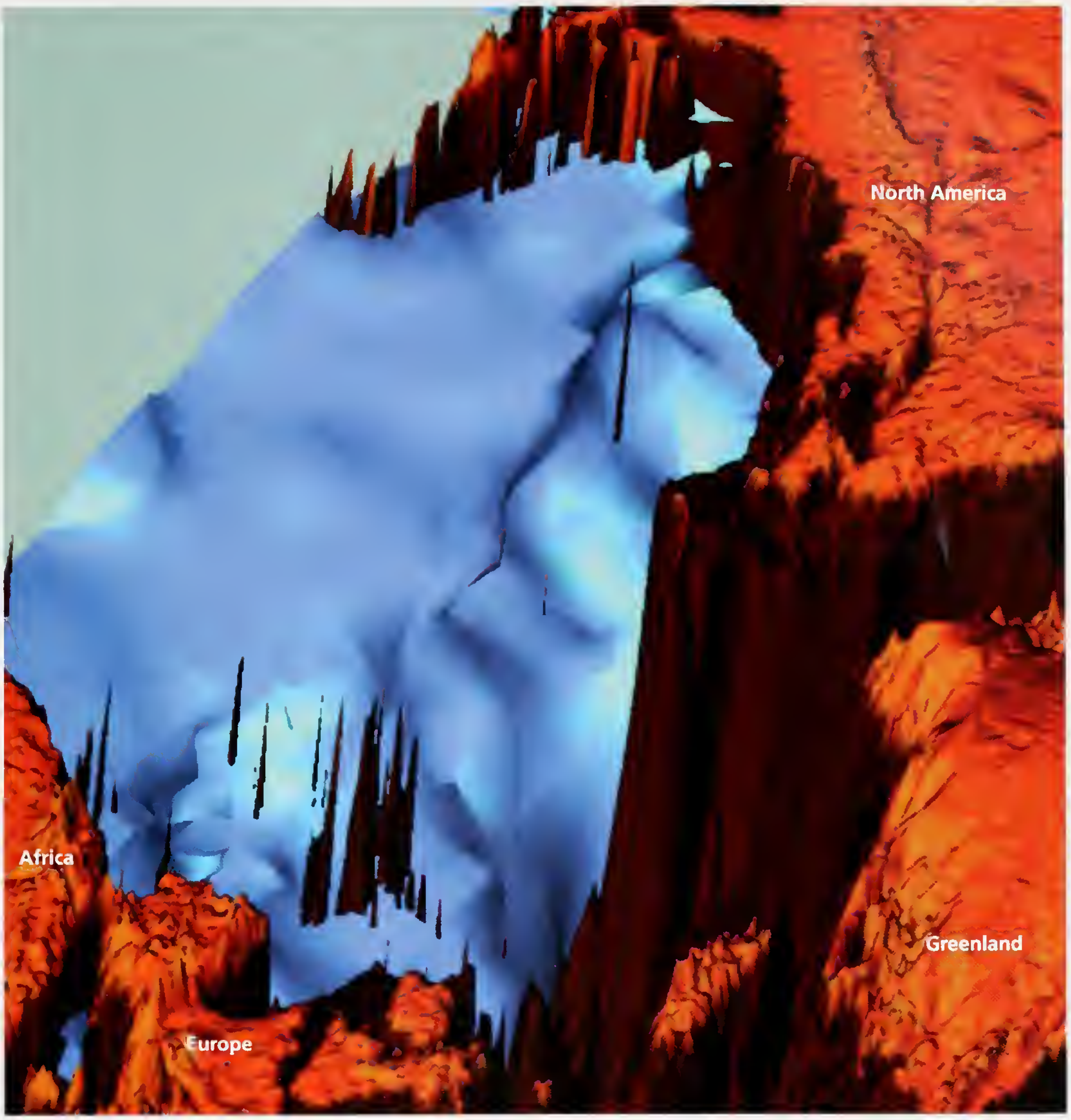
Our WHOI colleague Bob Pickart (see *Oceanus*, Spring 1994) has tracked the penetration of the extreme LSW along the deep western boundary current and Gulf Stream system off New England, and our University of Miami colleagues Rana Fine and Bob Molinari have recently (summer 1996) sighted this extreme LSW signal in the deep western boundary current off Abaco in the Bahamas—one of the most exciting and valuable results of their decade-long monitoring program at that location.

We are planning a 1998 field experiment to take advantage of this unique climate change signal by measuring the subtropical western basin's response to the LSW invasion at 24° N and 15° N. Because of the time delay observed in the subtropical response, we can be reasonably confident that we will be in the right places to measure this extreme LSW event, for we know through the continued efforts of our Canadian colleagues John Lazier and Allyn Clarke (Bedford Institute of Oceanography) that the LSW source continued to convect through the winter of 1995. They report a cessation of deep LSW convection in winter 1996. If that cessation is longer-lived than a single anomalous winter event, then we would expect it to appear as a subtropical climate change signal in 2000 to 2002.



Thickness difference fields (left column) and temperature difference fields (right column) were constructed by subtracting thickness or temperature in two consecutive time frames at each 1-degree square in the North Atlantic. The thickness represents the LSW density layer and temperature values are taken at a density surface in the middle of that layer. Green-blue colors indicate layer thickening and/or cooling in one time frame compared to the previous time frame; yellow-red colors indicate layer thinning and/or warming.

The authors' research is jointly funded by the National Science Foundation-sponsored World Ocean Circulation Experiment Program and the Climate and Global Change Program of the National Oceanic and Atmospheric Administration. The authors thank Terry Joyce for collaboration in producing the figure on page 26, James Hurrel (National Center for Atmospheric Research) for providing the most recent update of the NAO index data, and John Lazier for providing the Labrador Basin data for recent years and for his sustained effort for more than 30 years in maintaining critical time-series measurements in the hostile environment of the Labrador Basin.



A bird's eye view of the distribution of tritium in the North Atlantic. Picture yourself floating a few hundred miles above Norway, looking southwestward down at the North Atlantic. North America is in the top right corner of the view, Greenland to the lower right, and parts of Europe, Great Britain, and Africa are visible on the lower left. The spikes are ocean islands. The blue "blanket" is the 1 Tritium Unit isosurface (surface of constant tritium measured in 1981). (One Tritium Unit equals one tritium atom to 10^{18} hydrogen atoms.) Underneath this blanket lies water that has not been appreciably ventilated (in contact with the atmosphere) while water above this level has been ventilated since the 1960s.

Transient Tracers Track Ocean Climate Signals

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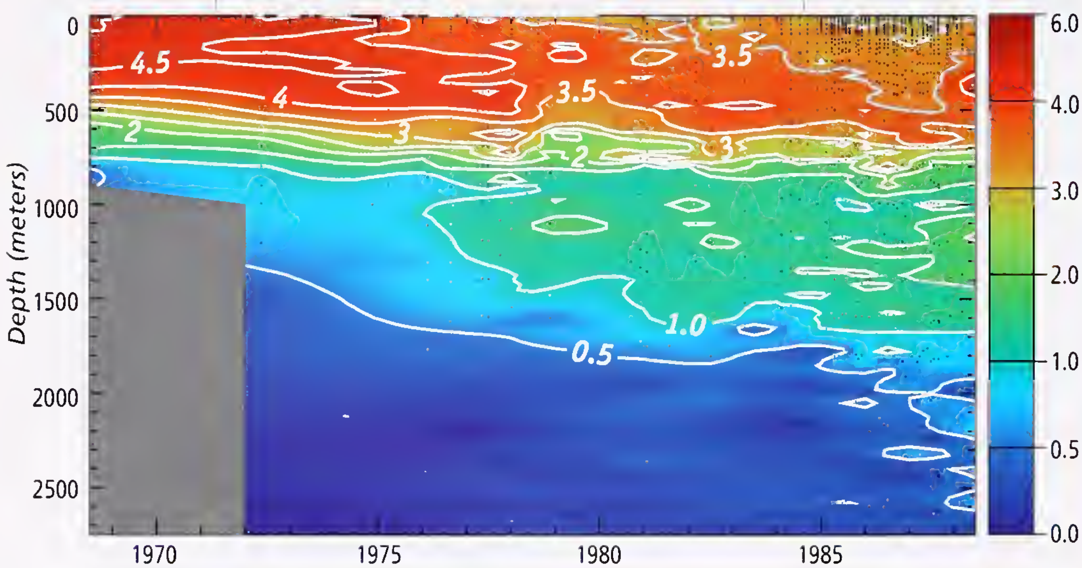
Transient tracers provide us with a unique opportunity to visualize the effects of the changing climate on the ocean. They trace the pathways climate anomalies follow as they enter and move through the ocean and give us valuable information about rates of movement and amounts of dilution. This knowledge is important for developing ocean-climate models to predict long term climate changes.

Humankind's activities have resulted in the release of a number of globally distributed substances into the environment. These substances enter the oceans, and, although they have little, if any, impact on the environment, they travel through and "trace" the biological, chemical, and physical pathways of the ocean. The distributions of these "tracers" change with time. For example, isotopes created by atmospheric nuclear weapons tests in the 1950s and 1960s were introduced in a pulselike fashion, while atmospheric concentrations of chlorofluorocarbons (CFCs), which threaten the earth's ozone layer, have been increasing with time. We refer to these substances in the ocean as "transient tracers" because their distributions are evolving.

Transient tracers are valuable tools for studying ocean climate. First, because they are new to the ocean environment, they are indicators of "ocean ventilation." Ventilation is the imposition of atmospherically derived properties on water masses. For example, waters in contact with the atmosphere will have dissolved oxygen concentrations increased to equilibrium values with the atmosphere. Providing their time history in the atmosphere is known and the manner in which they are transferred to the ocean is understood, they can be used to construct and test models of ocean ventilation and circulation. Observations of their distributions in the ocean and time series measurements of how they change with time are powerful tools: They provide direct visualization of climate changes, and they trace the pathways along which ocean climate perturbations propagate into the oceans. That is, changes in characteristics and volumes of water masses due to climate variations ultimately influence deeper, more isolated regions of the oceans. How these changes move to the deep ocean from regions of contact with the atmosphere must be understood. This process is an important mechanism whereby the oceans couple to the atmosphere on longer time scales, and probably plays a role in determining the interannual to decadal variations in global climate.



A time series of tritium in the Sargasso Sea near Bermuda. The plot of tritium vs. depth and time shows the sudden arrival of tritium at intermediate depths (1,000 to 1,500 meters) in the late 1970s, and at deeper depths (2,000 to 2,500 meters) in the late 1980s. These events correspond to the onset of cooling at these levels, and signal the arrival of newly ventilated waters in response to climate changes farther north.

Observations of tracer distributions provide information on processes that are very difficult to observe any other way. Mixing and dilution, for example, play a dominant role in the southward transport of material along the deep western boundary of the North Atlantic. It has long been known that newly ventilated North Atlantic Deep Water travels southward in a concentrated current, hugging the western edge of the Atlantic basin. Although direct current measurements indicate velocities of tens of centimeters per second, the actual average propagation rate of tracers down the western boundary is only one or two centimeters per second. This is because there is a tremendous amount of entrainment and mixing associated with water recirculating within the rest of the basin. The mixing slows the progress of tracers and climate anomalies. Transient tracers are perhaps the only tools for measuring the amount of interior exchange and downstream propagation rates.

Tritium: the Cold War Legacy

It is said that every cloud has a silver lining, and that seems to be true even if it is a mushroom cloud. Although the atmospheric testing of nuclear weapons released alarming amounts of radioactive debris into the environment, and caused untold damage to both the environment and human health, it also provided oceanographers with some unique tools to study ocean circulation and ventilation. We have had the opportunity to observe the entry of these substances into the oceans, and to see how they are moved around by physical, chemical, and biological processes.

One of these bomb-produced tracers is tritium, a radioactive isotope of hydrogen. There is very little natural tritium in the world (the entire global inventory would only weigh a few kilograms!), but several hundred kilograms were created in the hydrogen bomb explosions. This tritium was injected into the stratosphere, almost immediately oxidized to water, and fairly rapidly rained out onto the surface of the earth. Since it is chemically bound up as part of the water molecule (it is, after all, hydrogen), tritium is an ideal tracer of the hydrologic system. Further, since the bulk of the atmospheric weapons testing was done in the northern hemisphere, most of the tritium was deposited in the high latitude northern hemisphere. Thus it is an ideal tracer of ventilation and water mass formation in the North Atlantic.

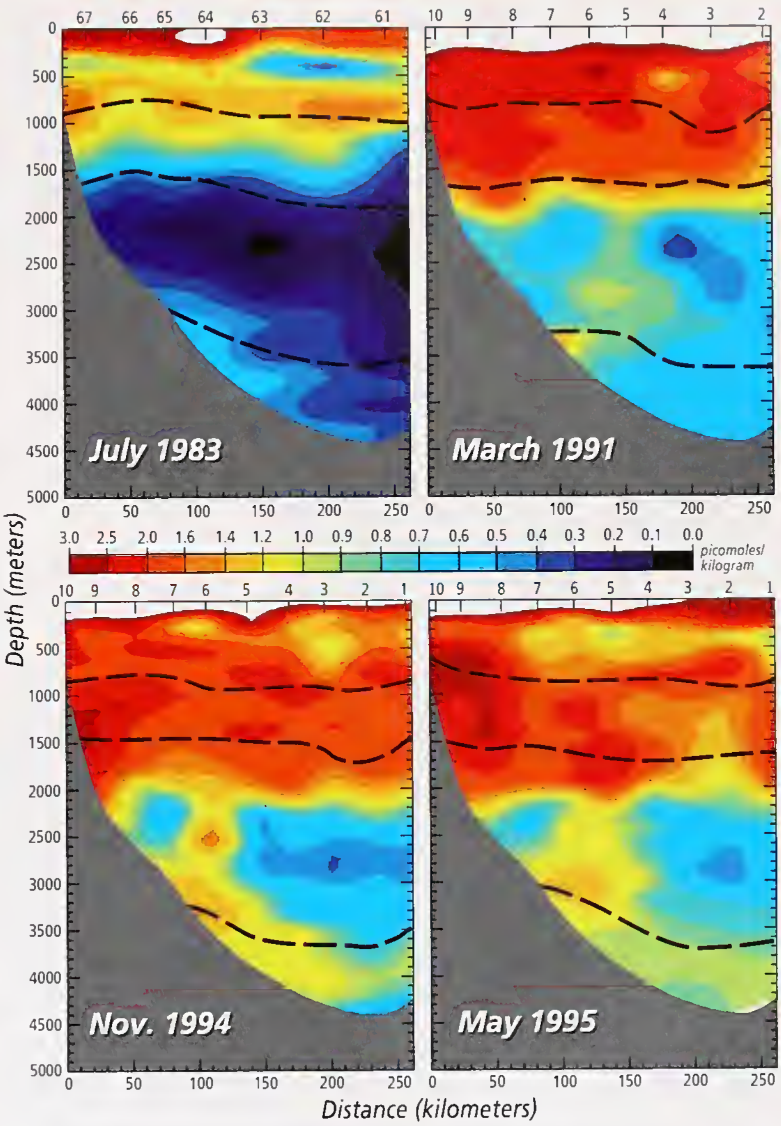
We can see this in the figure on the previous page, which provides a bird's eye view of tritium distribution in the North Atlantic in 1981. Picture yourself hovering somewhere over Norway, at an altitude of a few hundred miles. You are looking southwestward and downward on an isosurface of tritium in the North Atlantic. An isosurface is the two-dimensional analog of a contour line on a map, shown here in a three-dimensional ocean. The blue "blanket" you see in the picture is the 1 Tritium Unit isosurface, where we find a ratio of 1 tritium atom to100,000,000,000,000,000 hydrogen atoms. This isosurface corresponds to about 5 or 10 percent of the maximum surface water concentrations of tritium during the mid 1960s, when it was at its peak. All the water beneath this blanket has remained relatively isolated from the tritium invasion, and, conversely, all the water above this blanket has been at the sea surface, exposed to the atmosphere, and thus ventilated or otherwise involved in interaction with the surface ocean in the 15 to 20 years between the bomb tests and this survey.

The blanket lies at about 500 to 1,000 meters depth in the subtropics, but deepens to 1,500 to 2,000 meters just south of the Gulf Stream off the New England coast. This is the effect of the Gulf Stream recirculation, a tight gyre that effectively ventilates the upper part of the ocean in this region. There is also a fold extending southward from this region at about 1,200 meters depth, marking the intrusion of intermediate depth waters toward the tropics. Most notably, however, is the dramatic dive that the "blanket" takes to the north, disappearing into the ocean floor. The track along which this happens parallels the Gulf Stream Extension/North Atlantic Drift. All the waters north of this line have been ventilated to the ocean floor on 10 to 20 year time scales. This is a powerful statement regarding the time scales of ocean ventilation, and has profound implications concerning how rapidly climatic variations can propagate through the oceans.

We can see this in yet another way. The figure at left is a plot of tritium vs. depth for a time series near Bermuda from the late 1960s to the late 1980s. The tritium data has been adjusted for decay to the same date (January 1, 1981) to allow us to more clearly see the time trends. The most obvious trend is the downward propagation of a tritium maximum (deeper red) from the surface in the late 1960s to about 400 meters depth in the late 1980s, a downward penetration rate of 18 meters per year. However, from the perspective of climate change, the most important signal is the sudden increase in tritium (green) at about 1,500 meters in the late 1970s and at 2,500 meters in the mid 1980s. Both of these features correspond to the onset of significant cooling events seen in the deep water at this station. The correspondence between the sudden tritium increases and cooling offsets is highly suggestive of significant changes in deep water ventilation at those times. Indeed, if we could take another "picture" of the tritium blanket shown in the figure on page 29, we would see that it has been pushed further downward and southward by a climatic event.

Another Kind of Cold War Legacy

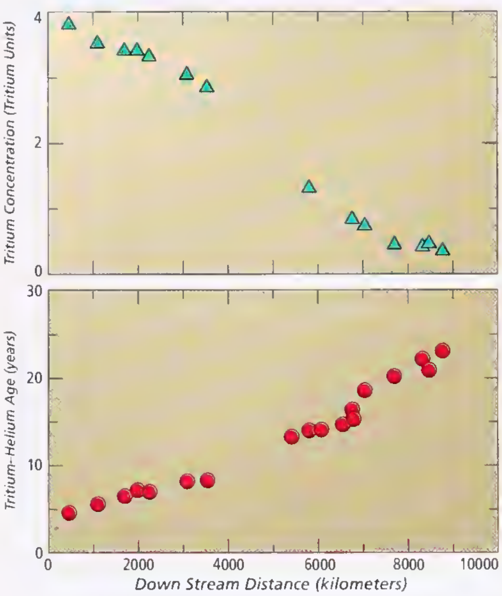
The development and manufacture of chlorofluorocarbons (CFCs) for use in refrigerators and air conditioners (and later as spray can propellants) seemed like a good thing at the time: CFCs were easy to manufacture, nontoxic, chemically inert, and stable. Production, use, and ultimate release of CFCs into the atmosphere increased annually in an almost exponential fashion from their introduction in the 1930s. The unfortunate influence of these compounds on the ozone layer, however, has lead to international reduction in their manufacture and use. In 1990, the US and 55 other nations agreed to end CFC production by 2000. Meanwhile, however, oceanog-



Four chlorofluorocarbon (CFC) sections taken at various times along 55° W south of the Grand Banks. Note the absence of any significant CFC signal at the depth of the Labrador Sea Water (about 1,500 meters depth) in 1983, but the sudden flooding of these depths with CFCs in the later sections, as newly formed Labrador Sea Water flows around the Grand Banks and into the Sargasso Sea. These changes correspond to the tritium increases seen in the Bermuda time series (see figure opposite).

raphers have found another "silver lining" in this ecological cloud, which has permitted us to study ocean ventilation and circulation: Waters that have been in contact with the atmosphere in the past few decades have taken up some of these compounds, and hence have been labeled in a distinctive way. Thus the distribution of CFCs in ocean water provides us with important clues regarding the pathways of newly formed water masses.

In the 1970s and early 1980s, there was not much winter time convection and formation of Labrador Sea Water. In fact, tracer sections (lines of stations) taken across the Deep Western Boundary Current to the south showed a decided lack of newly ventilated Labrador Sea Water. This hiatus is somehow related to the complex interplay between changing climatic conditions in the area and the freshwater outflow and budgets of the Arctic. The late 1980s and early 1990s have heralded a dramatic change in climatic conditions in the Labrador Sea. These changes have resulted in the production of a large amount of Labrador Sea Water, which is now invading the ocean interior. You can see this beginning to happen in the figure on the previous page, a time series of CFC sections made along 55° W south of the Grand Banks. Labrador Sea Water occurs in these sections at a depth of about 1,500-2,000 meters (the middle heavy dashed line). Notice that there was very little CFC-11 in this water in the 1983, although there is a CFC tongue at a shallower level characteristic of waters that are formed in the southeastern corner of the Labrador Sea (the shallowest heavy dashed line). Below the Labrador Sea Water core, there is a weak but detectable CFC core in waters characteristic of Denmark Straits Overflow water (marked here by the deepest dashed line). Combined, these three water masses form the Deep Western Boundary Current system of the North Atlantic, and are responsible for the southward transport of newly ventilated waters.



The downstream evolution of tritium (upper panel, in tritium units) and tritium-helium age (lower panel, in years) vs. distance in the core of the deep western boundary current. Note the approximately tenfold reduction in tritium content in the Deep Western Boundary Current core due to dilution with older, surrounding deep water, and the linear increase in age downstream. The age increase is consistent with a mean speed of about 1.5 centimeters per second.

However, in the 1990s, there is a sudden increase in the amounts of CFCs in the Labrador Sea Water core, as well as a steady increase in the deeper core associated with waters from the Denmark Straits overflow. This increase is continuing through the 1990s and is direct evidence of the newly ventilated waters' arrival. This again is a signature of the penetration of climatic anomalies into the ocean interior.

While the 55° W sections capture the invasion of the newly formed waters into the northern Sargasso Sea, the pathway southward is not a simple one. The Deep Western Boundary Current is not a continuous ribbon of flow extending all the way from the Grand Banks to the equator, but rather a composite consisting of series of interconnected gyres lined up along its path. A fluid parcel that passes by the Grand Banks may spend most of its time looping through these gyres, and only part of its time in the Deep Western Boundary Current. This is why the mean propagation speed of tracers down the western boundary is only 1 to 2 centimeters per second, while velocities in the actual core of the Deep Western Boundary Current are 10 to 20 centimeters per second.

The figure at left is a plot of tritium and tritium-helium age in the core of the Deep Water Boundary Current vs. distance downstream from its origin. We see that the core becomes progressively older (about 20 years in 10,000 kilometers) corresponding to a speed of about 1.5 centimeters per second. Notably, the tritium concentration in the core decreases more than tenfold downstream, partly due to decay, but largely due to dilution and mixing with older, tritium-free waters. This process of mixing is an important mechanism for ventilating the abyssal ocean. It's through this process that climate anomalies make their way into the deep ocean.

Thus the transient tracers are telling us something very important about the propagation of climatic changes into the deep ocean. They highlight the pathways and give us the rates of movement and dilution in the ocean. This information is valuable because the ocean provides the long term memory and feedback in the coupled ocean-atmosphere-climate system, and is the key to beginning to make long term predictions in our ever changing climate.

The research discussed in this article was supported by the National Science Foundation and the Office of Naval Research.

Bill Jenkins started life as a nuclear physicist but drifted into environmental sciences out of a secret yearning to become a forest ranger. Not having a good sense of direction, and fearing black flies, however, he ended up as an oceanographer on Cape Cod. He joined the WHOI Chemistry Department (now the Department of Marine Chemistry and Geochemistry) in 1974.

Bill Smethie's interest in oceanography began during childhood summers spent at his grandfather's log cabin on the Virginia side of the Potomac River. He embarked on his first oceanographic cruise at age 7 when he attached a makeshift sail to his inner tube and set sail for the other side of the river. His doting aunts prevented him from making it to the other side, but ever since he has had a never-ending curiosity for what lies beyond the horizon. He joined the Geochemistry Division of Lamont-Doherty Geological Observatory in 1979.

New Data on Deep Sea Turbulence Shed Light on Vertical Mixing

Rough Seafloor Topography Has Far-Reaching Effect

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The global thermohaline circulation is basically a wholesale vertical overturning of the sea, driven by heating and cooling, precipitation and evaporation. (Changes in temperature=*thermo*, changes in salinity=*haline*.) Bottom waters move equatorward from their high-latitude regions of formation (the cold limb of the circulation), upwell, and return poleward at intermediate depth and/or the surface (the warm limb). As the bottom waters are colder than the overlying waters, this circulation is responsible for a large fraction of the ocean's poleward heat transport. In addition, these flows often redistribute fresh water, as the northward and southward moving waters generally have different salinities.

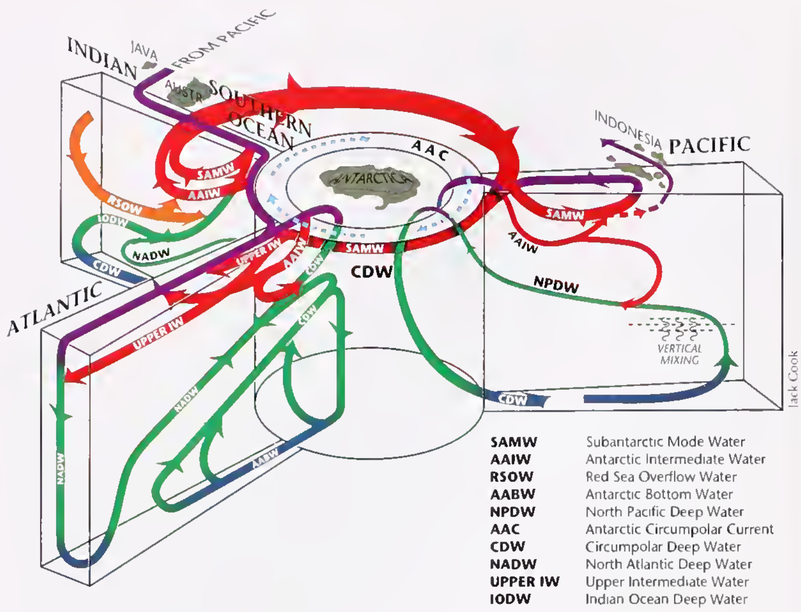
These oceanic heat and water transports play a significant role in Earth's climate. The earth gains heat from the sun at low latitude, and radiates heat back to space about the poles. To maintain a quasi-steady state, the ocean–atmosphere system must carry heat from low to high latitude. At mid-latitudes, where the poleward heat flux is maximum, the oceanic and atmospheric contributions are about equal. One component of the atmospheric heat transport involves evaporation, water vapor transport, and its subsequent condensation. Net north/south water vapor transport in the atmosphere is balanced by liquid water transport by rivers and ocean currents.

For almost 200 years, since the writing of Count Rumford in 1797, there has been a basic understanding of the cold limb of the thermohaline circulation. The combination of atmospheric cooling, evaporation, and, in some cases, salt rejection during the formation of sea ice causes surface waters at high latitudes to become sufficiently dense that they sink to the ocean bottom. These newly formed deep waters subsequently spread horizontally within the constraints of the seafloor's bathymetry to renew the deep waters found in the interiors of the world's oceans. There are two principal formation sites for dense bottom water: the Greenland and Norwegian Seas of the northern North Atlantic Ocean, and around the Antarctic continent, particularly within the Weddell Sea. Together, these source regions export some 20 to 30 million cubic meters per second of bottom water to the other ocean basins. (For comparison, the chiefly wind-driven Gulf Stream, Kuroshio, and Agulhas Currents carry in excess of 100 million cubic meters per second within horizontal circulations.)

The processes involved with the return limb of

Ellyn Montgomery

The principal tool for work described in this article is the high resolution profiler. It records temperature, salinity, pressure, and horizontal velocity 10 times per second on descent to the ocean floor, then returns to the surface. For a detailed discussion of the instrument's development, see the Spring/Summer 1995 issue of *Oceanus*.



Circulation schematic of the world's major water masses (also see inside front cover). Of concern here are the mixing processes that modify the bottom and deep waters within the cold-to-warm limbs of the overturning circulation.

the thermohaline circulation—the transformation of these bottom waters to lower density, and their upwelling and eventual return to the high-latitude cooling zones—are less well understood. An upwelling of deep and bottom waters is believed to be fed by the continual supply of new bottom water: Dense new waters intrude below older waters and force them upwards. The bottom water source strength of 20 to 30 million cubic meters per second translates into a globally averaged upwelling rate at mid-ocean depth of about 3 meters per year. This upwelling has both dynamical and thermodynamical implications.

To maintain a steady-state temperature distribution in the face of this upwelling of cold water, a compensating warming is required. This warming may be accomplished by internal mixing of the deep ocean. Models exploring the thermodynamic balance between the downward diffusion of heat associated with mixing by turbulent eddies and the upwelling of cold water were published by Klaus Wyrtki (University of Hawaii) and Walter Munk (Scripps Institution of Oceanography) in the mid 1960s. At about the same time Wyrtki's and Munk's papers appeared, Henry Stommel, considering the dynamical effects of deep upwelling, proposed the existence of abyssal gyre circulations involving poleward deep flow in the ocean interiors fed by a series of western boundary currents. These boundary flows ultimately connect to the high-latitude bottom water formation sites. Twenty years later Frank Bryan (National Center for Atmospheric Research) published a study of an idealized, three-dimensional ocean model showing a direct relationship between the intensity of the vertical mixing and the strength of the thermohaline overturning circulation. These theoretical ideas linking diffusion, upwelling, and the deep current systems have guided research on abyssal circulation for the past three decades.

But how much vertical diffusion is there in the oceans, and what processes sustain it? Munk's application of his model to data from the North Pacific Ocean required a downward diffusive heat flux about 1,000 times larger than that caused by molecular diffusion (the process whereby differences in temperature or concentration of a dissolved substance are removed by the random motion of molecules). More recent studies concerning vertical diffusive heat fluxes in semi-enclosed basins also required downward diffusive heat fluxes thousands of times greater than those due directly to molecular diffusion. All of the researchers involved invoke turbulent mixing as the mechanism supporting these large diffusive heat fluxes.

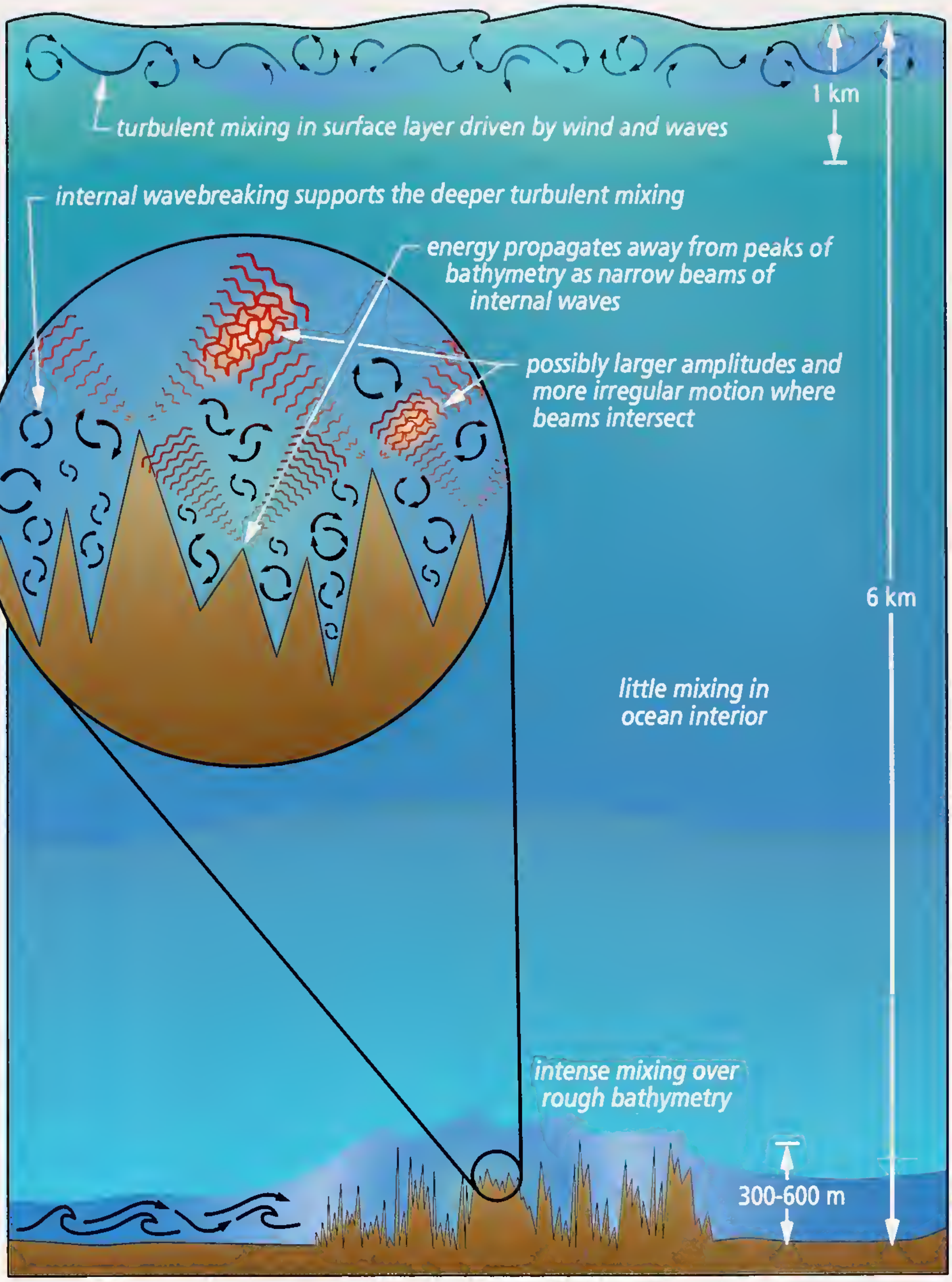
Ocean turbulence is the focus of a subgroup of physical oceanographers specializing in microstructure, that is, temperature and velocity structures occurring at spatial scales directly influenced by seawater's molecular viscosity and thermal diffusivity—typically around one centimeter. These scientists have extensively sampled the upper ocean in recent years. Apart from the surface layer (which is actively mixed by wind and waves), the shallow ocean margins, and highly sheared flows like the equatorial undercurrent, the microstructure data suggest turbulent diffusive fluxes some ten times smaller than the studies mentioned above. This seeming discrepancy caused some to question the models used to deduce the intensity of vertical diffusion from microstructure data, and whether sufficient data had been gathered to adequately describe ocean microstructure. Relatively weak mixing in the upper ocean away from boundaries was, however, recently confirmed by a nontoxic chemical tracer release experiment in the Northeast Atlantic led by Jim Ledwell.

The apparent contradiction between microstructure-based and indirectly determined estimates of vertical diffusion might actually reflect a real difference with depth in the ocean. Part of the problem is that the indirect estimates of vertical mixing have been derived for the deep ocean, while the bulk of the microstructure observations are from the top 1 kilometer of the ocean. Ray Schmitt, Kurt Polzin, and I have recently addressed this issue with a series of cruises on which we acquired full-ocean-depth profiles of temperature and velocity microstructure. We find evidence of enhanced turbulent mixing in the deep ocean near the bottom, particularly in regions where the bottom is rough. The zone of enhanced mixing extends upward to several hundred meters above the bottom, a span much greater than that of the traditional bottom boundary layer, a roughly 10-meter-thick, vertically homogenized layer that is maintained by bottom-generated turbulence. Our data also show strong internal waves at these sites, and we believe the enhanced mixing is sustained by the breaking of these internal waves, which are both generated at and reflected from the rough bottom.

These observations also document striking horizontal patterns in the turbulent mixing at depth. Our current study (a joint microstructure-tracer experiment in collaboration with Jim Ledwell) is now underway in the Brazil Basin, the region where Nelson Hogg and colleagues inferred significant vertical diffusion from a heat budget for the bottom waters. In the interior of the basin where the bottom is smooth, the microstructure data imply turbulent fluxes less than a tenth of Hogg and colleagues' basin-averaged value. In contrast, above the rough flanks of the Mid-Atlantic Ridge in the eastern third of the basin, we deduce turbulent fluxes greater than their figure.

We find that the horizontally averaged turbulent heat flux for our study region, based on the microstructure data now in hand, is in near accord with that derived from the bottom water heat budget. Our results suggest that vertical diffusion in the deep ocean is dominated by turbulent mixing near rough bathymetric structures, a refinement of Munk's hypothesis that it occurs generally near the bottom. Greater average turbulent fluxes may be achieved at depth than in the upper ocean because a larger fraction of the deep ocean is in close proximity to the bottom. Spatially variable mixing in turn implies existence of horizontal circulations to distribute modified waters from these mixing zones throughout deep basins. Moreover, given the dynamical links between mixing, upwelling, and circulation, our findings hint that the deep gyres predicted by Stommel might be highly distorted in the real ocean.

The scientific community is just beginning to document the intensity and patterns of mixing in the ocean abyss. It is not surprising that mixing in ocean climate models has so far been generally taken as spatially uniform. Much work remains to be done, both observational and theoretical, to fully understand the role of turbulent mixing in the ocean's thermohaline circulation.



A schematic drawing of turbulent processes at work in the ocean.

The research discussed in this article was supported by the National Science Foundation. Initial development of the High Resolution Profiler was supported by the Department of Defense and the Office of Naval Research.

Attraction to the sea and ocean science began for John Toole with a keen interest in sailing. He maintains an eclectic research program at WHOI that includes study of basin-scale circulations and the processes of ocean mixing. Developing understanding of the cold-to-warm limb of the thermohaline circulation represents a synthesis of research supported by grants from the National Science Foundation and the Office of Naval Research. With WHOI colleagues and his wife (and chief foredeck crew), he also continues to campaign sailing race courses through the summer, as research cruises and meetings permit.

Computer Modelers Simulate Real and Potential Climate, Work Toward Prediction

Combining Equations and Data Pushes Computers' Limits

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Although weather forecasting is accepted by the public as part of daily life, oceanic forecasting is not yet so advanced. There are, however, successful examples of oceanic forecasting—one is the newly developed skill to predict El Niño/Southern Oscillation (ENSO) events, largely due to improvements in ocean modeling (see following article).

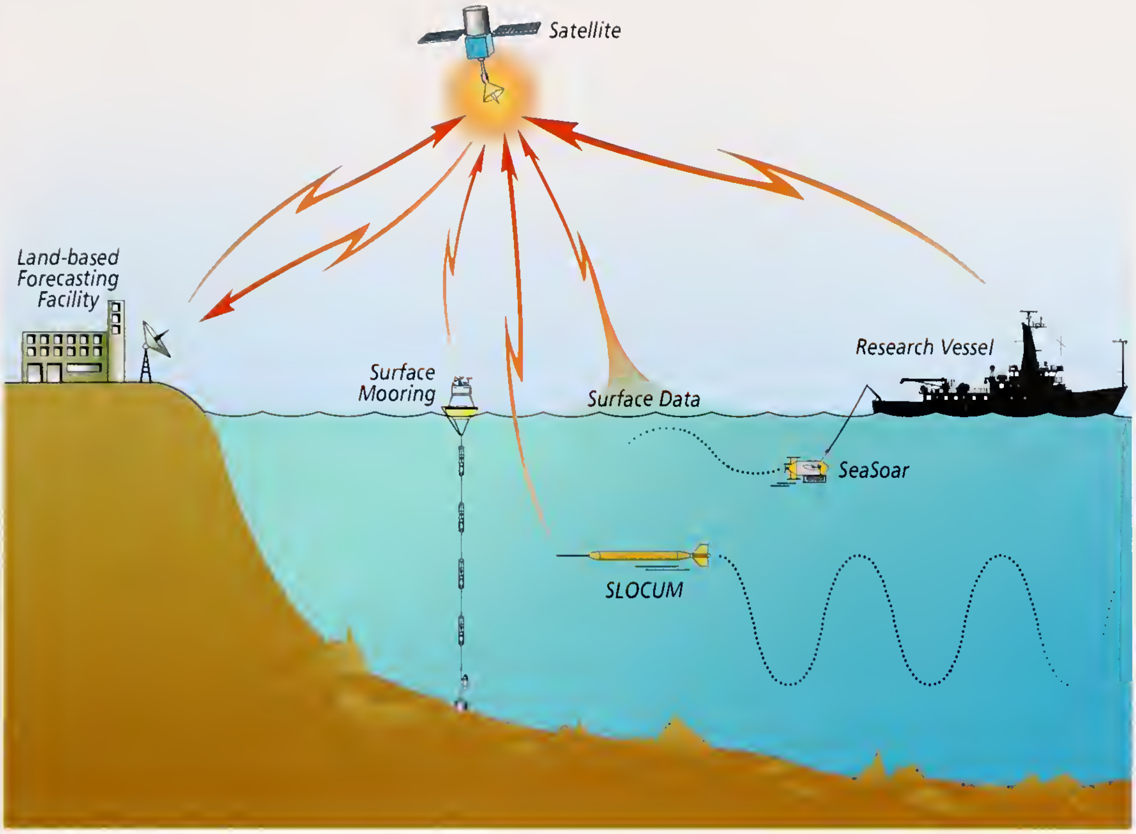
In 1982 and 1983, Eastern Australia and Indonesia experienced the century's worst drought, which led to devastation in agricultural regions and rain forests, and even to loss of hundreds of lives. These were just some regional impacts of what is now known as the most severe ENSO event on record, an anomalous warming of sea surface temperature in the eastern Tropical Pacific Ocean that occurs once every three to seven years. The change in oceanic conditions associated with ENSO is usually accompanied by atmospheric shifts, and together these phenomena lead to droughts in some parts of the world and flooding in others. It is estimated that total worldwide damage caused by the 1982–83 ENSO was more than $10 billion.

Authors Rui Xin Huang, right, and Jiayan Yang collaborate on ocean process study and climate prediction models.

Another climate variation, the North Atlantic Oscillation (NAO), a shift of atmospheric pressure fields between Iceland (65° N) and the Azores (40° N) on decadal time scales, is known to change weather conditions in Europe and North America (see Box on page 13). ENSO and NAO are just two examples of how natural climatic fluctuations can dramatically affect the world economy and our daily lives. Earth's climate changes ceaselessly, and it will surely continue to evolve, possibly in a more complicated manner due to increasing atmospheric concentrations of greenhouse gases. Thus there are pressing reasons to improve our understanding of severe climate variations, such as ENSO and NAO events, and even to predict them before they occur so that the public can be informed and policy makers can prepare for possible natural disasters. Because the future is unobservable, we must rely on numerical models for such forecasting.

Geologic studies of Earth's history show that the world ocean has changed profoundly over time. Modern observations indicate that there have been noticeable changes in world ocean circulation even during recent decades. As our knowledge advances, so does our understanding of the ocean's importance in the climate system. Driven by wind stress as well as heat and freshwater fluxes, oceanic currents redistribute heat across the globe and regulate our climate. The ocean's enormous capacity to store heat also buffers climate changes. Since the ocean and the atmosphere exchange momentum, heat, and fresh water across their interfaces, variation in one fluid system can lead to changes in the other, often in a chain reaction that amplifies initially small deviations. Many climate phenomena, such as ENSO, result from such interactions, which can occur over a wide spectrum of time scales. So, even though the weather can be forecast for a week without considering oceanic circulation, climate on time scales longer than a month must include the ocean.

Temporal evolution and spatial variation of the ocean are constrained by physical laws and such external forcing fields as wind stresses and surface buoyancy fluxes. The essence of climate



The authors envision a forecasting center that would receive near-real-time data from a variety of sources by satellite transmission for constant updating of ocean climate models. The data sources might include those shown here. The surface mooring transmits meteorological data as well as information from the string of instruments below it. Slocum, described on page 6, surfaces once a week or so at the top of its trajectory to transmit temperature and salinity records from ocean depths, and SeaSoar data on a variety of upper ocean characteristics is beamed from the ship. Data collected by satellites would include sea surface elevation, wind stress, temperature, and perhaps salinity.

modeling is to integrate the dynamic equations for these climate components forward in time, starting with conditions that are often based on actual observations. The basic idea of computer simulation is to organize physical equations into a net of grids arranged to cover a spatial domain, such as the tropical Pacific Ocean for ENSO predictions, or the global oceans for carbon cycle assessments, and then predict the climatic state at each grid in the future based on its initial condition and its subsequent interactions with surrounding grids as the conditions in each change. Though the evolution of a climate event is unrepeatable and beyond our control, computer simulations can be repeated many times by varying the mathematic representation of conditions and forces at work in each grid. Thus, numerical models are very powerful tools for testing scientific hypotheses and for examining important climate processes.

One good example is a study by Frank Bryan, who conducted numerical experiments in the early 1980s while a graduate student at the Geophysical Fluid Dynamics Laboratory in Princeton, NJ. By running an idealized model for the Atlantic Ocean, he showed that deep water formation in the North Atlantic could be shut off by a strong salinity perturbation in the subpolar basin. If such changes were to take place, the North Atlantic's poleward heat flux would be substantially reduced, and the European climate would be remarkably less mild. His modeling results are consistent with a paleoclimatic record that shows deep water formation was interrupted about 12,000 years ago in an event known as the Younger Dryas when melted glacial water flooded the subpolar North Atlantic Ocean, resulting in Northern Hemisphere cooling and even reduction in the deglaciation process.

The accuracy of a numerical model depends on how well and how realistically it approximates boundary conditions, external forcing, and key processes that govern the real climate system. The ideal model would use a very fine spatial grid and a small integration time step to resolve spatial and temporal structures of all important physical processes in the system. For instance, mesoscale eddies, whirling parcels of fluid typically 40 to 200 kilometers wide in the subtropics, play significant roles in redistributing momentum, heat, salts, and other dissolved matter in the ocean. Excluding such processes will definitely lead to inaccurate model representations of the oceans. However, most of the current climate models use resolutions (spacing between two adjacent grids) on the order of 100 kilometers or coarser, too coarse to explicitly resolve the spatial structures of mesoscale eddies.

Increasing the horizontal and vertical resolution of the models 10 times requires increasing the number of grid points 1,000 times. In addition, the allowable time step for maintaining the numerical calculation's stability will be at least 10 times smaller (the time step should be smaller than the grid size divided by the maximum velocity). Thus, we need a computer that is 10,000 times faster and has 1,000 times more memory. For such high resolution, even the fastest computers, such as the 128-processor CM5 computer, which reaches a speed of 3 gigaflops (3 billion float point operations per second), cannot yet accommodate a long-term global simulation. Thus one key aspect of climate modeling involves how to accurately represent important processes that cannot be explicitly resolved due to model resolution limits. This is called the subgrid-scale parametrization.

Another important process that requires care is the direction along which mixing occurs. In many ocean general circulation models (OGCMs), especially those formulated in fixed spatial grids, mixing in a model grid is represented by some form of averaging its properties with those in surrounding grids. In the real world, mixing is most likely to occur along constant density surfaces so that the mixing processes do not work against the buoyancy. Recent work by James McWilliams and Peter Gent and their colleagues at the National Center for Atmospheric Research has significantly improved the performance of ocean models that use spatially fixed grids.

Rapidly developing computer technology allows climate modelers to work at ever finer resolution as they aim explicitly to model the structures and temporal evolution of eddies. For instance, Albert Semtner and his colleagues at the Naval Postgraduate School in Monterey, Califomia, have used an OGCM with a horizontal resolution of about 10 kilometers to study circulation in the Arctic Ocean and the Greenland and Norwegian Seas. Their eddy-resolving model captures many observed frontal structures, such as sharply defined features often associated with strong jets, that coarse resolution models have not been able to capture.

There are two major categories in ocean climate modeling, process studies and climate predictions. Process studies aim to understand important processes that operate the real climate system, to identify mechanisms that give rise to climate variations, or to explain particular patterns observed in the real world. Such studies often involve a hierarchy of models, from simple ones to full, three-dimensional models. Climate predictions, like numerical weather forecasts, attempt to determine future climate states based on available knowledge about how the climate system evolves in time. Climate predictions always benefit from progress in process studies. For instance, tremendous advances in process studies of tropical air-sea interactions in the 1980s led to great success in predicting ENSO events a year ahead of time. Simple models play very active roles in process studies. For example, the late Henry Stommel used a very simple two-box model to elucidate how the distinct difference between air-sea fluxes of heat and fresh water lead to multiple equilibrium states in the oceanic thermohaline circulation. This seminal work laid the foundation for our understanding of the stability and variability of the Atlantic overturning circulation. More comprehensive models, which can resolve mesoscale eddies and include ocean-atmosphere interactions, have been used to verify Stommel's work and to gain further understanding of the oceanic thermohaline circulation.

Climate prediction models must prove they can describe observed climate evolutions in the past before they can be trusted for future predictions. Therefore, modelers need observations to calibrate and verify their models. Unlike atmospheric data sets, oceanic observations have relatively short records and sparse coverage in space. New observing technologies, like satellite remote sensing, acoustic tomography, and the long-lived floats that Ray Schmitt describes on page 6, will certainly expand the observing capacity and support climate modeling. A global observational network is likely to be a combination of satellite-borne instruments (which can measure sea surface elevation, wind stress, temperature, and perhaps salinity); automatic instruments, such as buoys and data-transmitting floats; and traditional shipboard instruments. Data collected by these instruments will be sent to a land-based forecasting center, where the most powerful supercomputers will merge current oceanographic data and forecast oceanic conditions for the near future. With the rapid advance of computer technology and our understanding of ocean physics, oceanic forecasting will eventually become a reality—perhaps early in the 21st century, marine and climate forecasting will become routine.

The research discussed in this article was supported by the National Science Foundation and the National Oceanic and Atmospheric Amdinistration's Global Climate Change Program.

Rui Xin Huang's primary research interest is large-scale oceanic circulation, including wind-driven gyres and thermohaline circulation. When he was in high school, his dream was to become an inventor like Edison. Through a long and winding road, he came to Woods Hole, and found oceanography an exciting field. He also likes swimming, gardening, and, above all, puzzles and games.

During his graduate student and postdoctoral years, Jiayan Yang was interested mainly in tropical air-sea interaction. He decided to take "a short break" away from the tropics to do a small, high-latitude oceanography project when he was a postdoctoral fellow at the University of California, Los Angeles. He has stayed in high-latitude oceanography ever since. He moved from Los Angeles to New England to get a bit closer to (though still far way from) sea-ice margins. In his leisure time, he likes hiking, swimming, biking, and karaoke.

The El Niño/Southern Oscillation Phenomenon

Seeking Its "Trigger" and Working Toward Prediction

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The El Niño/Southern Oscillation (ENSO) phenomenon, an eastward shift of warm water in the tropical Pacific and associated effects on the atmosphere, is at the heart of global interannual climate variability. The just completed, decade-long Tropical Ocean/Global Atmosphere (TOGA) program was dedicated to understanding and working toward predicting ENSO by bringing together oceanographers and atmospheric scientists in a coordinated observational and numerical modeling research program. TOGA has not answered all the questions: We have not uncovered the physical mechanisms of the elusive ENSO "trigger" nor have our best coupled air/sea numerical models been as successful in predicting the rather irregular ENSO signal of the 1990s as they were in predicting the regular events of the 1980s and hindcasting the events of the late 1960s through the 1970s.

Prediction is the ultimate goal of ENSO research. It is also the ultimate test for an ENSO model and the theory underlying the model. During the last decade, a number of forecast models have shown predictive skills in both retrospective and real time forecasting, and they are now being used for routine ENSO prediction. Nevertheless, the skill of even the best available models is far from perfect, and there is still considerable room for improvement in modeling, observation, and forecasting techniques.

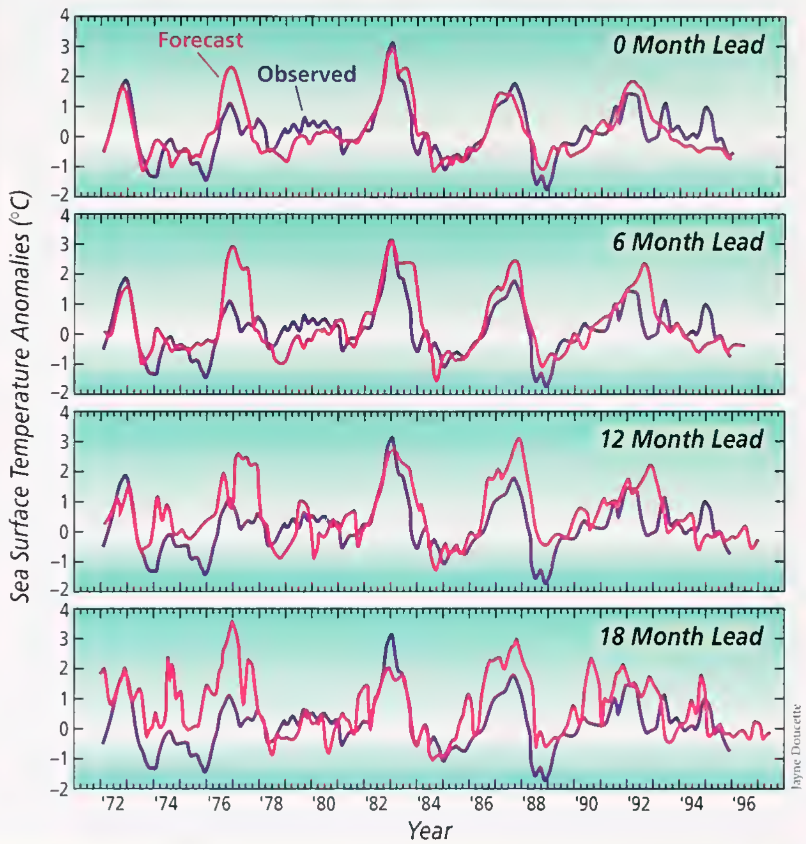
Factors that limit the current skill of ENSO forecasts include:

- an inherent limit to predictability because of the chaotic and random nature of the natural system,
- model flaws such as oversimplified physics,
- gaps in the observing system, and
- flaws in the way the data is used (data assimilation and initialization).

It seems likely that the inherent predictability limit for ENSO is years rather than weeks or months, though more theoretical study is needed in this area. The observing system is improving, but still far from satisfactory. Thus a challenge facing the modelers is to improve model forecasts by making the most reasonable and efficient use of available data.

In the past few years much effort has been devoted to assimilating various observational data into the initial state of forecast models. The most common approach is to improve the initial ocean conditions by assimilating observations of sea surface temperature, thermocline (region of rapid temperature decline) depth, or sea level into an ocean model prior to coupling it with an atmosphere model. One problem

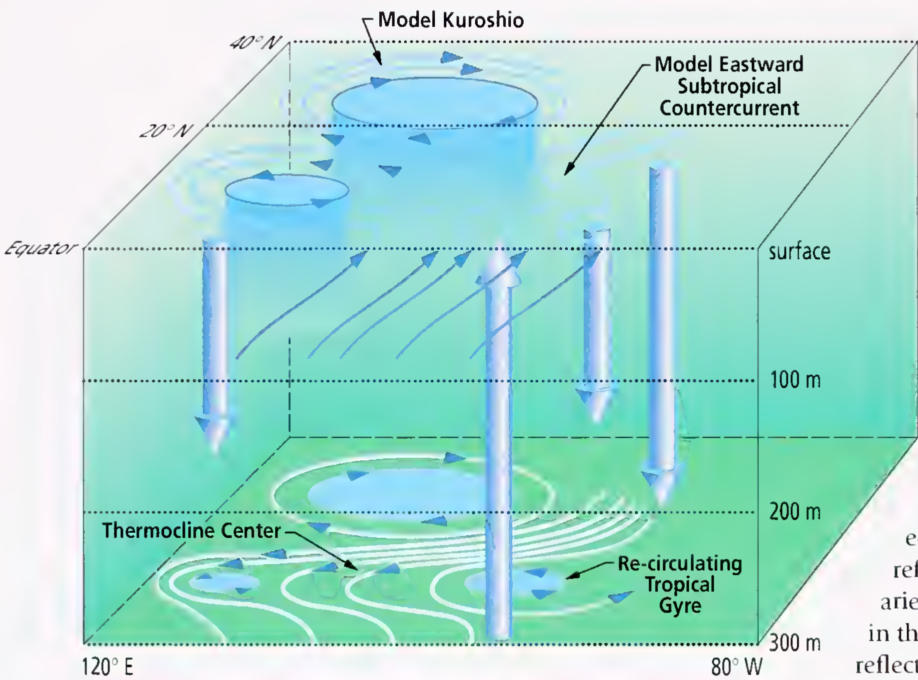
Time series of observed (red) and forecast (blue) El Niño sea surface temperature anomalies. Forecasts with 0, 6, 12, and 18 month leads are shown in different panels, and the observed anomalies are repeated from panel to panel.



with this approach is that no attention is paid to the ocean-atmosphere interaction during initialization, so the coupled system may not be well balanced initially and may experience a shock when the forecast starts. A new initialization/assimilation procedure significantly improves the predictive skill of one of our most promising coupled models, which was constructed by Mark Cane and Steve Zebiak (Lamont-Doherty Earth Observatory).

In the new methodology the model is initialized in a coupled manner, using a simple data assimilation scheme in which the coupled model wind stress anomalies are "nudged" toward observations. The new procedure improves the model's predictive ability as measured by a variety of statistical scores. It also eliminates the so-called "spring prediction barrier," a marked drop of skill in forecasts that try to predict across the boreal spring, found in many previous ENSO forecast systems. The success of the new initialization procedure is attributed to its explicit consideration of ocean–atmosphere coupling, and the associated reduction of initialization shock and random noise.

As an example, the forecasts made by the improved model are compared to observations in the figure on page 39 in terms of the sea surface temperature anomaly averaged over an area in the eastern/central equatorial Pacific (5° S to 5° N and 90° W to 150° W). The model is capable of forecasting ENSO more than one year in advance. The large warming and cooling events in the 1980s are particularly well predicted. However, the model does a poorer job for the 1970s and 1990s: The 1976–77 event is largely overpredicted, and the short warm episodes in 1993 and late 1994 are missed.



This diagram illustrates weather pathways in the North Pacific subtropical/tropical upper ocean and the main horizontal gyres and meridional-vertical cells of the region's ocean circulation.

Although the predictive skill of this model is most likely limited by its highly reduced physics, the skill of more sophisticated coupled ocean-atmosphere general circulation models presently does not exceed that of the model described above, at least in terms of the tropical Pacific sea surface temperature. In order to predict the global impact of ENSO, a two-tiered approach appears to be reasonable: A physics-simplified, coupled model is first used to predict tropical sea surface temperature fields, and these fields are then used as boundary conditions for a more-complete-physics, global atmospheric general circulation model to predict the global distribution of atmospheric disturbances. Scientists are rigorously pursuing this kind of research.

A second area of progress concerns improved understanding of the coupling between different depths and different regions of the ocean. A popular ENSO paradigm that emerged in the late 1980s was based on the observed, rather regular rythms of ENSO conditions during a span of 25 years before 1990. The "delayed oscillator" mechanism emphasizes eastward-propagating equatorial wave processes,* westward-propagating off-equatorial signals, and their asymmetric reflections at eastern and western boundaries respectively. Despite the irregularities in the 1990s ENSO, this wave propagation/reflection paradigm is still compelling; it can accomodate irregularities in the ENSO signal by combining the tropical signal with longer-term variability in the subtropics.

A number of studies have sought to understand how tropical variability is linked to the mid latitudes. Ocean circulation may provide the links via several different pathways that are summarized schematically above. These are not simple, direct north-south flows; the existence of vigorous zonal current systems complicate the picture. In the upper layers of the ocean, upwelled waters along the equator flow into the subtropics, mainly through the mid-latitude western boundary current (the Kuroshio). There is an additional interior ocean pathway, through the eastward Subtropical Countercurrent, that more directly feeds subtropical sites where sur-

*Flow along the equator tends to be trapped there. The Coriolis force, due to the earth's rotation, turns water that flows south back to the north and water that flows north back to the south. Because of this trapping, physical oceanographers recognize the equator as a waveguide, where coherent signals or waves can be seen to propagate east-west for long distances.

face water moves deeper into the ocean. These interior pathways are associated with a recirculating tropical gyre in and just below the mixed layer in the northeastern tropics. Below the mixed layer, thermocline water from the subtropics to the tropics zigzags almost zonally across the basin, succeeding in flowing toward the equator only along zonally narrow, southward flowing conduits. The low-latitude western boundary currents serve as the main southward circuit for the subducted (water moving from the surface to depth), subtropical thermocline water.

A model constructed by the authors also indicates important direct flow of thermocline water through the ocean interior, confined to the far western Pacific (away from the low-latitude western boundary currents) along 10° N. These southward flowing waters are then swept eastward by the North Equatorial Countercurrent, finally penetrating to the equator in the central and eastern Pacific. The water pathways in the subtropical thermocline essentially reflect the surface gyre circulation.

Along with our colleagues Ronghua Zhang (University of Rhode Island) and Antonio J. Busalacchi (NASA Goddard Space Flight Center), we have examined the interannual variability of these subtropical/tropical pathways and found important propagating *subsurface* ENSO signatures in the subtropical Pacific. There appears to be continual movement of subsurface, basin-scale anomalies that can then affect sea surface temperature (SST) anomalies, especially in sensitive regions where the thermocline is shallow. These SST anomalies can then trigger coupled air/sea interactions. A clear pattern of moving anomalies is less obvious at the sea surface. The systematic subsurface propagation is reminiscent of the delayed oscillator: eastward along the equator, westward off the equator with apparent further propagation along the eastern and western boundaries. Off the equator, subsurface propagation of anomaly patterns initiates an SST anomaly in the North Equatorial Countercurrent regions of the western Pacific, which then intensifies and moves into the equatorial waveguide, consistent with the mean water pathways found above. We speculate that this could be a mechanism for initiating coupled, air-sea interactions that can begin to evolve as an ENSO event. The cycling time of the subsurface anomaly patterns may determine the ENSO's frequency. We look forward to continuing our investigations to solidify these assertions.

One challenge for the newly established Climate Variability (CLIVAR) program will be to uncover the ENSO triggering mechanism and enable intelligent design of a long-term ocean and atmosphere monitoring system. CLIVAR is the oceanographic and atmospheric scientific community's new program of climate prediction. Its focus is on understanding the coupled air/sea system's variability on seasonal-to-interannual-to-interdecadal time scales for the purpose of determining predictability, and then prediction. Those observations would then feed into coupled air/sea numerical models for the purpose of long lead time forecasting, much like the present-day weather forcasting systems. However, the interannual ENSO signal does not exhibit a simple ryhthm; there are clearly influences on longer (decadal) time scales that need to be considered. There are clues as to what those signals might be (for example, the North Atlantic Oscillation—see page 13), but we are still in the early stages of identifying these signals.

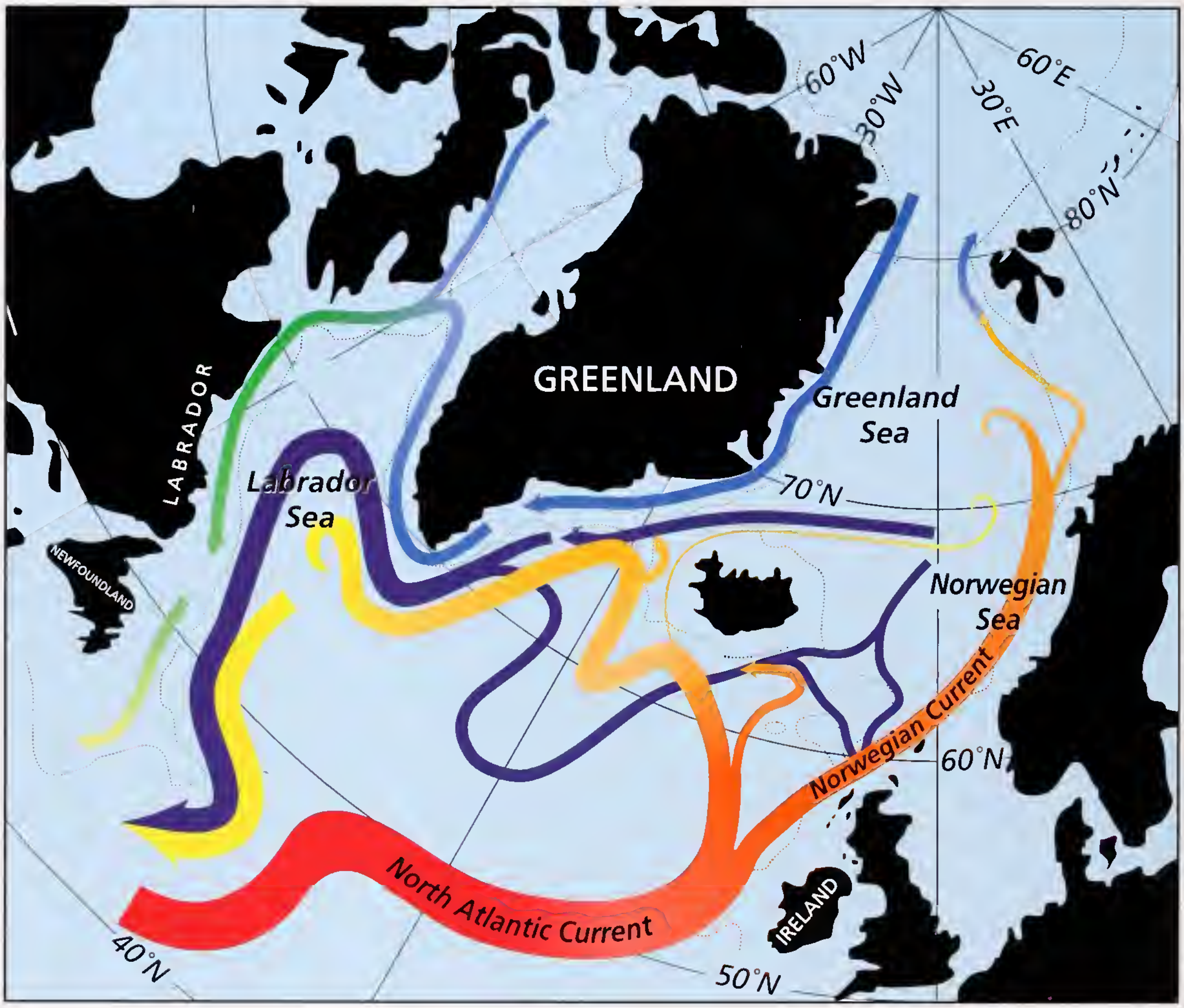
The natural system is not easily divided according to time scales; it is a fully nonlinear system. If we are to understand and eventually predict global interannual variability, we must not limit ourselves to monitoring the air/sea system over a few interannual cycles. Permanent monitoring systems are needed. It is the primary charge of CLIVAR to help design such a monitoring system while, at the same time, supporting the evolution of the numerical prediction systems that will issue the forecasts.

Julia Neander, NOAA/PMEL

Servicing an Autonomous Temperature Line Acquisition System (ATLAS) mooring of the Tropical Ocean Global Atmosphere (TOGA) program's Tropical Atmosphere-Ocean (TAO) Array in the Pacific Ocean. ATLAS moorings measure surface winds, air temperature, relative humidity, sea surface temperature, and subsurface temperature to depths of 500 meters.

The authors' ENSO research is supported by the National Oceanic and Atmospheric Administration, the TOGA Program on Seasonal to Interannual Prediction, and the National Aeronautics and Space Administration.

Lew Rothstein started his career as a physical oceanographer on the beautiful campus of the University of Hawaii. He is now a professor at the University of Rhode Island and an editor of the Journal of Geophysical Research. *Dake Chen is also a physical oceanographer by training. He worked with Lew on various tropical ocean models at the University of Rhode Island before he joined the senior staff of the Lamont-Doherty Earth Observatory last summer. Both of them are fond of building computer models of the ocean and atmosphere, not only for scientific research but also for fun.*



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